

Master's Thesis

**Master's Degree in Energy Engineering
Specialisation in Renewable Energies**

**Development of an Integral Model
for RENE based Electrical Microgrids
located in Remote Rural Communities**

Author:
Director:
Call:

Eng. Valeria Karina Moreno
Dr. Eng. Oriol Gomis Bellmunt
June 2018



Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona



Abstract

The lack of electricity is one of the main problems in the development on the rural communities. The access to electricity can be achieved through the implementation of electric microgrids. A microgrid is one of the most indispensable elements of smart power systems to improve the reliability and resilience of energy supply.

Off-grid microgrids are among the most viable solutions for electrification of remote areas, islands, and regions to which extension of the main utility grid is costly. Expansion planning of off-grid microgrids requires a concrete business model to ensure that affordable energy is supplied to customers [1]. It is necessary that these microgrids will be efficient, economic and reliable.

In order to achieve the expected microgrids characteristics, the purpose of the present Master's Thesis is the development of an integral model for the sizing and costing of Low Voltage Direct Current (LVDC) Electrical Microgrids, based on Renewable Energy (RENE) Technology. The microgrid sizing implies the development of a technical model and the Microgrid costing implies the development of an economic model. The main objective in the development of both models is to find an optimal configuration for the PVSHS, achieving a balance between the technical and the economical characteristics of the microgrid.

The mentioned Model it is based on a real case of study which implements Photovoltaic Solar Home Systems (PVSHS) in a LVDC Microgrid. The Microgrid is located in a Remote Rural community, where the access to the electrical main Grid is not always possible. In the present case of study the real location is in the city of Dhaka, capital city of Bangladesh.

The corresponding methodology is based in the development of a MATLAB Code, which includes a general Sizing Method for Microgrids and the general Economic Method, which achieves the calculation of the correspondent LCOE of the technology. Several scenarios will be analyzed, taking into account different parameters of the Microgrid namely different cable configurations, number of PV Panels, voltage drop and cable sections.

The main results obtained in the Sizing Methodology, were in terms of the number of PV Panels and the section and the length of Cable utilized. Due to the little amount of energy necessary to cover the demand, it is possible to use a minor number of PV Panels than the consider in previous studies. Besides that, the importance of the cable in final the design and in the cost of the microgrid is crucial. For this reason, two different cable configurations were analyzed. In terms of the Economical Analysis the main result is related with the obtained LCOE value and the inputs utilized in order to calculated it. A new LCOE model is developed for this kind of microgrids due to the correspondent expenditures can not be obtained from general reports.

Key Words: Low Voltage Direct Current (LVDC), Microgrids, Photovoltaic Solar Home Systems (PVSHS), Levelized Cost of Energy (LCOE).

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Glossary

Symbols

<i>BCa</i>	Battery Capacity
<i>BoS</i>	Balance of System
<i>BoSC</i>	Balance of System Cost
<i>BoSE</i>	Balance of System Electric
<i>BoSS</i>	Balance of System Structure
<i>CAPEX</i>	Capital Expenditures
<i>FC</i>	Fixed Costs
<i>FClc</i>	Fixed Costs Local Currency
<i>LCOE</i>	Levelized Cost of Energy
<i>LVDC</i>	Low Voltage Direct Current
<i>MPPT</i>	Maximum Power Point Tracking
<i>NREL</i>	National Renewable Energy Laboratory
<i>OM</i>	Operation and Maintenance
<i>OMAC</i>	Operation and Maintenance Annual Costs
<i>OMAClc</i>	Operation and Maintenance Annual Costs Local Currency
<i>OMC</i>	Operation and Maintenance Costs
<i>OPEX</i>	Operational Expenditures
<i>PV</i>	Photovoltaic
<i>PVP</i>	Photovoltaic Panel
<i>PVPC</i>	Photovoltaic Panel Cost
<i>PVPP</i>	Photovoltaic Panel Power
<i>PVPPp</i>	Photovoltaic Panel Power Peak
<i>PVSHS</i>	Photovoltaic Solar Home System

Introduction

For the developing world, providing and maintaining access to the electricity is the main driver for developing off-grid microgrids, as this technology provides the most economical solution for electrification of remote areas. In fact, microgrids could become an alternative to grid extensions if the decrease in cost trends persists [6].

The development of an integral model for the sizing and costing of Low Voltage Direct Current (LVDC) Electrical Microgrids, based on Renewable Energy (RENE) Technology will be developed. The microgrid sizing implies the development of a technical model and the Microgrid costing implies the development of an economic model. The main objective in the development of both models is to find an optimal configuration for the PVSHS, achieving a balance between the technical and the economical characteristics of the microgrid.

There exist a difficulty of comparing costs for PVSHS in Bangladesh with other PVSHS benchmarks, like the OECD Countries. The scale, purpose and configuration of the systems all differ significantly.

They are small systems, with typical capacities of 20 W to 100 W, that provide off-grid electricity services. In contrast, in OECD (Organization for Economic Co-operation and Development) countries small-scale solar PV rooftop systems are almost always grid-connected rooftop systems in the 1 kW to 20 kW range.

The scales of the systems also are dramatically different. PV Systems can be classified based on their size as follows: Utility-Scale PV, Commercial PV and Residential PV.

Compared to Bangladeshi PVSHS, some of the larger OECD rooftop solar PV systems on residential houses would seem more like utility-scale projects, with sizes thirty to thousand times larger than that of an African SPVHS. Clearly, even though these are small systems, the economies of scale of the larger OECD systems and the absence of batteries means that per watt costs will be significantly higher for the small SPVHS used in Africa.

The scope of the present Master Thesis is the analysis of PV Solar Home Systems (PVSHS), which are included inside the Residential classification. Notwithstanding, even inside this classification, the correspondent system expenditures can achieve a big variation, which mostly depends on the size of the system, the country, the special taxes and policies, among others. For this reason it is necessary to differentiate the LCOE analysis making a new classification inside the Residential one:

- PVSHS bigger than 1 KW
- PVSHS smaller than 1 KW

The economic model will be developed taking into account the specific characteristics of both types of systems.

Methodology and Planning

The Master's Thesis is organised in chapters. In Chapter 1 an introduction to the topic is achieved, considering the main characteristics of the LVDC Microgrids, and the presentation of the state of the art for previous projects.

Through Chapter 2 a Technical Model is developed. The corresponding methodology is based in the development of a MATLAB Code, which includes a general Sizing Method for Microgrids.

In Chapter 3 it is expected to obtain an Economic Model for the Microgrid. The corresponding methodology is based in the development of a MATLAB Code for the general Economic Method, which achieves the calculation of the correspondent LCOE of the technology.

For Chapters 2 and 3 several scenarios will be analyzed, taking into account different parameters of the Microgrid namely different cable configurations, number of PV Panels, voltage drop and cable sections.

Chapter 4 and Chapter 5 develop the Budget and the Environmental Impact of the project. This chapters are elaborated at the same time than the of results and conclusions are obtained.

Finally, key conclusions are drawn. The following graphic it is a representation for the specific plan of the previous Methodology.

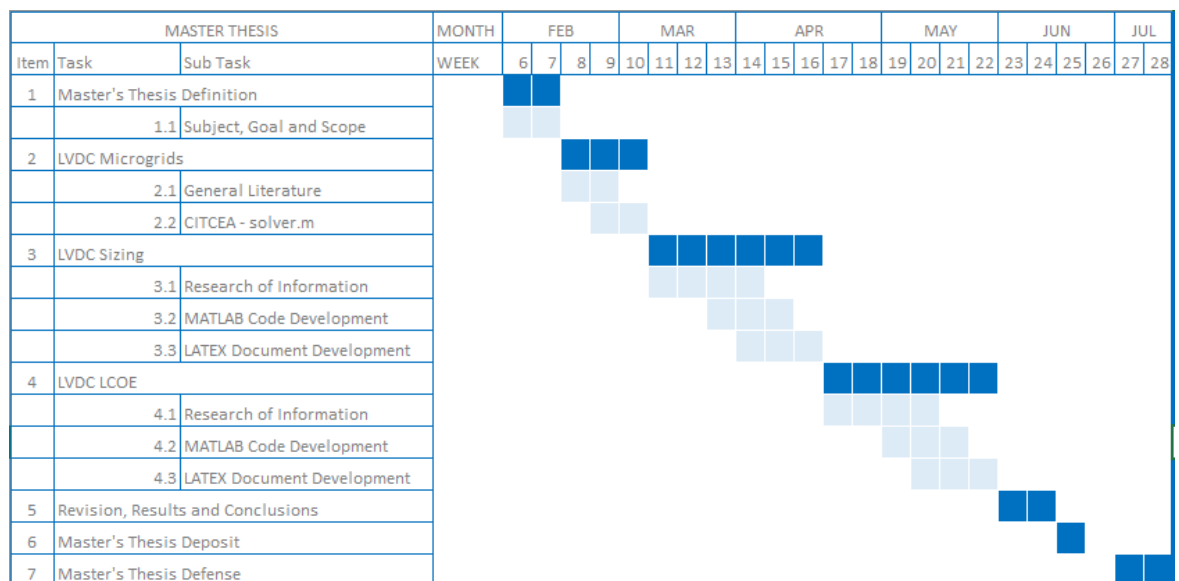


Figure 1: Planning and Programing

Chapter 1

LVDC Microgrids for off-grid electrification

1.1 Introduction

It is estimated that virtually 20% of the population of the world have no access to electricity. Traditional approaches to electrify rural areas include capital intensive infrastructures and large investments, while LVDC Microgrids, based on RENE Resources and Storage Systems can be easily implementable and can lead to cost effective solutions [7]. For the developing world, providing and maintaining access to the electricity is the main driver for developing off-grid microgrids, as this technology provides the most economical solution for electrification of remote areas. In fact, microgrids could become an alternative to grid extensions if the decrease in cost trends persists [8].

A microgrid is one of the main elements of smart power systems to improve the reliability and resilience of energy supply in distribution networks [8]. A microgrid is a group of interconnected distributed generation and demand entities within the clearly defined boundary to represent a single controllable entity in the utility that operates either in grid-connected or island mode.

The declining capital cost of renewable resources and energy storage promotes the application of such technologies to provide electricity for households and small communities [8]. The effects and objectives of implementing microgrids for off-grid electrification are quite different from the cases in which microgrids are operated in grid-connected mode and the utility grid is counted as the primary source. Off-grid microgrids mainly provide access to electricity for people who live in areas for which an extension of the grid cannot be performed with reasonable time and cost. Therefore, the impact of off-grid microgrids is not only measured by the reduction in the electricity cost in rural and remote areas, but also by the extent of improvement in residents quality of life.

1.2 Benefits of LVDC Microgrids

Direct current (DC) microgrids have the potential to increase the affordability of rural electrification in developing countries by reducing complexity, costs and by increasing total system efficiency [7].

With DC networks, the parallelization of generators is easier, avoiding complex synchronization algorithms, inverter final stage is not necessary, avoiding the associated investment and its losses. Furthermore output filters, that in alternate current (AC) network are designed for 50 or 60 Hz, become smaller (necessary to remove only the high switching frequency) with additional increase of system efficiency and decrease of power system costs [7].

Considering the load side, most of the efficient appliances are already DC loads. Additionally, the most efficient existing AC loads, as refrigerators, fans or air conditioner systems, are driven by inverters with a AC/DC converter first stage. In AC networks, there is a need for this first stage, whereas in DC networks, this conversion is not required [7].

Highly efficiency DC appliances have the potential to increase dramatically the affordability of DC networks used for rural electrification in developing countries by reducing the size of the required power systems. Considering an equal level of services, the use of highly efficient DC appliances can have, a remarkable impact on system cost reduction [7].

1.3 LVDC Microgrids in Bangladesh

Rural electrification is an integral component of poverty alleviation and rural development of a nation. In Bangladesh, Photovoltaic (PV) technology in the form of solar home systems (SHS) has been widely applied for rural electrification purposes [9].

Bangladesh is known to possess a good potential for renewable energy, particularly solar energy that is abundant and can fruitfully be harnessed. Several private entrepreneurs, Infrastructure Development Company Limited (IDCOL), some government agencies and a number of non-governmental organizations (NGOs) are working to install solar PV in rural Bangladesh to meet basic energy needs. The application of PV technology for rural electrification is indirectly increasing the income as well as the living standard of the rural poor [9].

1.3.1 SOLShare

Founded in 2014 and based in Dhaka, Bangladesh ME SOLshare Ltd. is a social enterprise that offers products and services contributing to the Global Goal 7: Affordable and Clean Energy for All.

They provide peer-to-peer solar energy trading platforms and pay-as-you-go solutions to low-income households seeking rural electrification and empowerment.

- Vision: Facilitate a climate resilient, equitable, and sustainable future for all where smart technology innovation is the enabler for rural empowerment
- Mission: Create a network. Share electricity. Brighten the future.

1.4 The Case of Study in Bangladesh

The LVDC Microgrid under study is shown in the next figure:

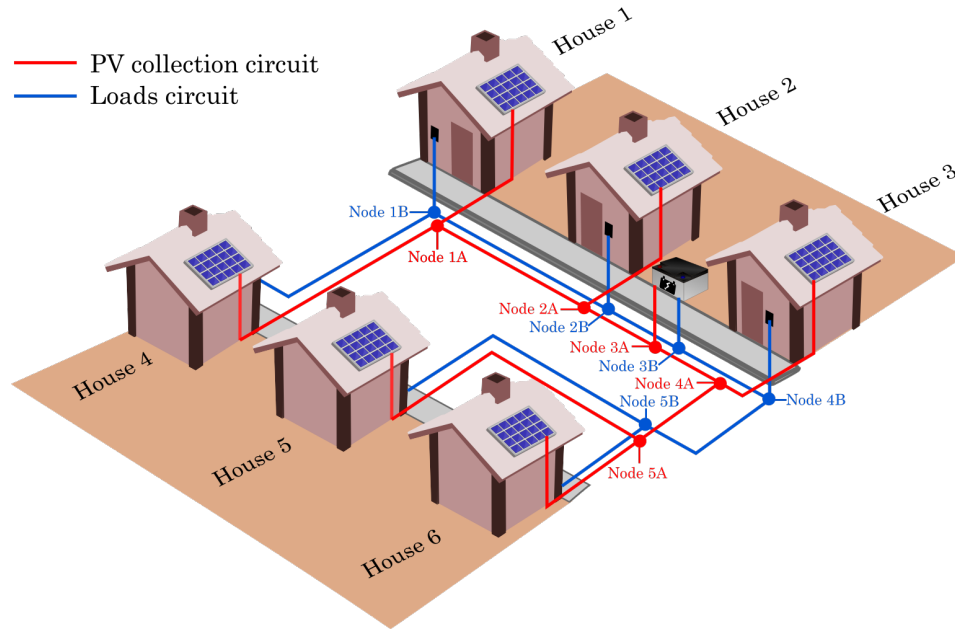


Figure 1.1: Drawing of the case study microgrid [2]

The Microgrid is composed of six Photovoltaic panels, one battery and six Tier 2 loads, which implies low consumption, no higher than 50 W and 4 hours a day maximum.

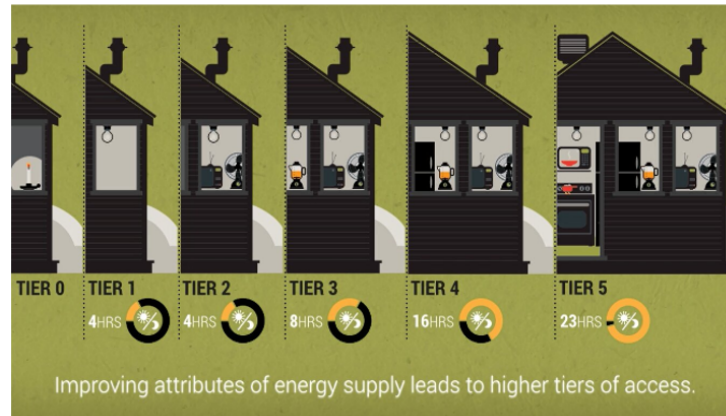


Figure 1.2: Tier 2 [3]

The electrical scheme of the LVDC Microgrid is represented in the following figure.

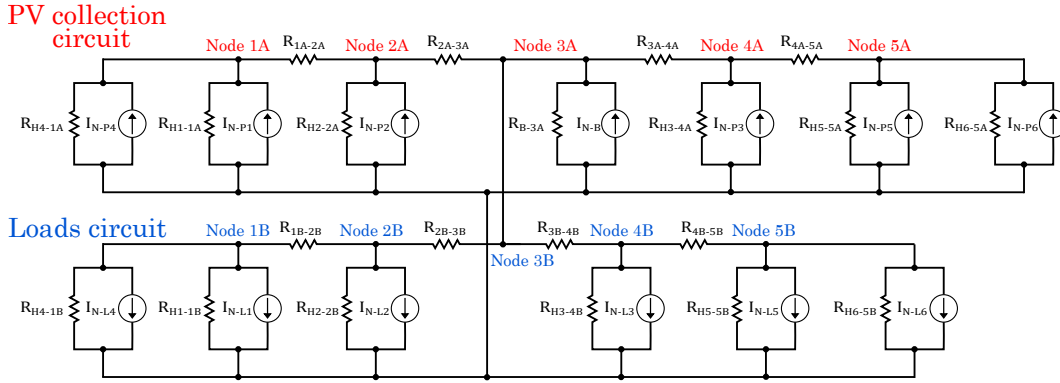


Figure 1.3: Scheme from the analyzed microgrid [2]

Photovoltaic panels parameters are detailed in Table 1.1. It is assumed that the microgrid location is Dhaka (Bangladesh). Then, the solar PV production is obtained based on this location considering the irradiation and temperature local conditions using NREL software PVWatts [10]. Besides, additional assumptions have been made [2]:

- The PV panel model used is the same for each of the houses
- All the PV cells receive the same irradiance
- The temperature of all the PV cells is equal
- The demand is equal for all the different households
- Grid nominal operation voltage is 12 V
- A load profile has been generated based on Tier 2 consumption data
- The allowed voltage deviation at the loads point of connection is $\pm 25\%$ of the nominal value
- The PV collection circuit and the loads circuit are equal (distances and cable sections)

Table 1.1: PV cell parameters [2]

Parameter	Value	Units
$I_{SC_{ref}}$	1.45	A
V_{oc}	22.2	V
R_S	1.0394	Ω
R_{SH}	2177.3561	Ω
G_{ref}	1000	W/m^2
n	1.3	-
q	$1.6022 \cdot 10^{-19}$	C
k	$1.3806 \cdot 10^{-23}$	J/K
T_{ref}	298.15	K
α	0.0048	C^{-1}
N_{cell}	36	-
I_{Pmax}	1.37	A

1.5 State of the Art: The solver.m

The present Master Thesis is developed based on the prior studies developed in [11] and [2]. The current developed MATLAB codes are directly related with the code developed in the cited papers, taking into account their main results.

The second article compares different topologies for Low Voltage DC networks that might be used in the electrification process of communities without access to electricity. These type of networks usually include distributed generation (mainly PV), energy storage (batteries) and loads in several houses. Currently, these grids are being built isolated from the AC network and without including any power converter to control the power ow [2].

A comparison between the typical converterless approach and three alternative topologies is developed, one including a DC/DC converter connected to the central battery, another including converters connected to the PV generation systems, and a third one including converters connected to each generation and storage system [2].

The main circuit parameters are detailed in the following Table:

Table 1.2: Parameters used for the case study [2]

Parameter	Value	Units
Cable section	4	mm ²
Resistivity	0.0171	Ω mm ² /m
Irradiance	1000 (Day) and 0 (Night)	W/m ²
Power per load	50 (full load) and 0 (no load)	W
Battery voltage	12	V
PV cells	6	-
Loads	6	-
Batteries	1	-

The results for this first topology (No Converters) are shown in Table 1.3. It can be seen that the PV panels work at an approximately 75 % of their nominal production, at full irradiance and full load conditions. Additionally, at full irradiance and no load conditions, Table 1.3 reveals that the power produced by the PV panels is similar to the full load and full irradiance case. Moreover, it can be stated that the losses represents approximately a 16 % of the power consumed when the loads are connected.

Table 1.3: Power flow results - No converters[2]

Parameter Name	$G = 1000$ W/m ²		$G = 0$ W/m ²		$G = 1000$ W/m ²	
	$P_L = 50$ W		$P_L = 50$ W		$P_L = 0$ W	
	Sum	Mean	Sum	Mean	Sum	Mean
P_{pv}	104.06 W	17.34 W	0 W	0 W	108.24 W	18.04 W
P_{load}	-300 W	-50 W	-300 W	-50 W	0 W	0 W
P_{bat}	240.7 W	240.7 W	350.66 W	350.66 W	-103.43 W	-103.43 W
Max V_{drop}	12.61 %	-	13.02 %	-	3.54 %	-
I_{max}	20.06 A	-	29.22 A	-	8.619 A	-
P_{loss}	44.76 W	-	50.66 W	-	4.34 W	-

Chapter 2

LVDC Microgrids: PVSHS Sizing

2.1 Introduction

The following methodology is based on [4]. The main objective is to find an optimized Photovoltaic Solar Home System (PVSHS) Sizing for the actual load demand in the studied houses. It will be important to compare different systems configurations in order to find some possible improvement points.

Besides, the methodology aims to compare different voltages levels of the battery and different sections of the cable, in order to find the optimal economic configuration.

The following graphic resumes the main steps followed in the development of the present methodology:

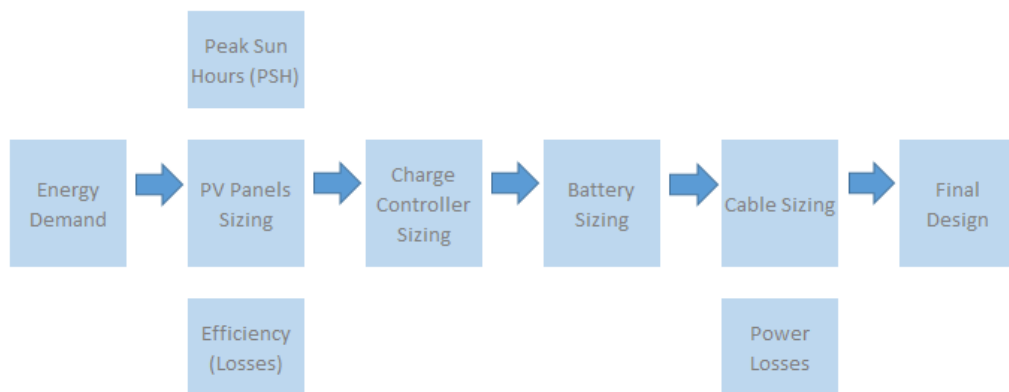


Figure 2.1: Sizing the LVDC Microgrid [4]

2.2 Methodology

2.2.1 Energy Demand

The first step in the present methodology is the calculation of the total energy demand for the studied houses.

The following graph provide information about the measured load data:

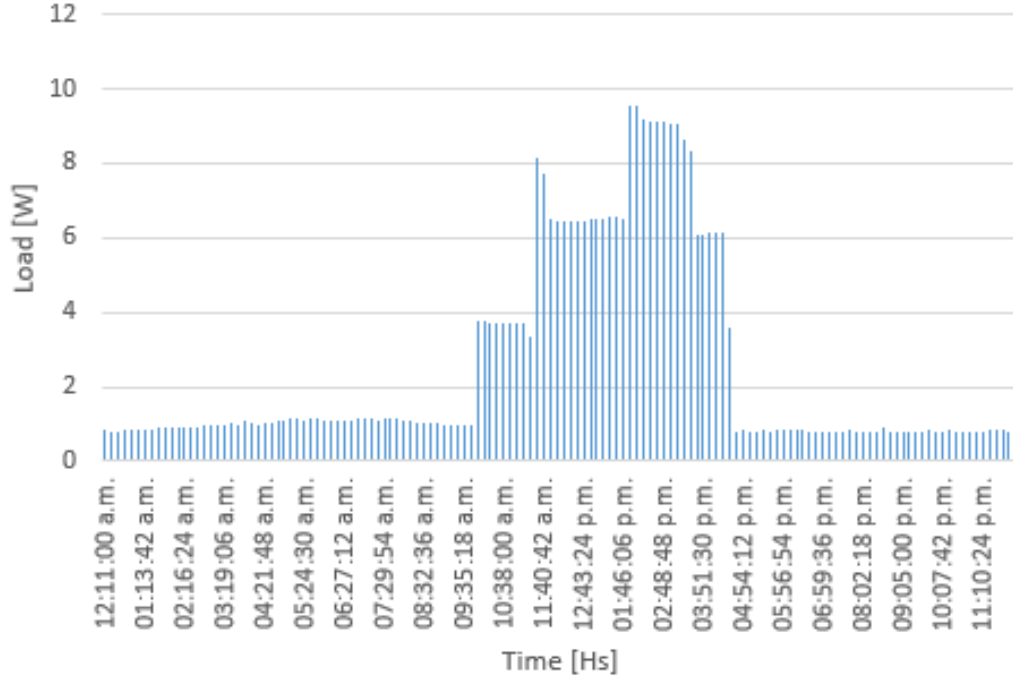


Figure 2.2: Load Data

Based on the previous measured data, the function `trapz` on Matlab allows to find the Daily Energy Demand for one house, which is measured in [Wh/day]:

$$DD = \text{trapz}(X, Y) \quad (2.1)$$

This is the amount of photogenerated energy expected by the system per day. Then the Total Daily Energy Demand can be obtained multiplying this value by six, taking into account the six houses of the project. Besides that, an annual value for this Demands is obtained multiplying both Daily values for the 365 days of the year [Wh/year].

$$DDT = DD * 6 \quad (2.2)$$

$$AD = DD * 365 \quad (2.3)$$

$$ADT = DDT * 365 \quad (2.4)$$

2.2.2 PV Panels Sizing

The PV array on a regular day should be able to supply the DDT of Photogenerated energy calculated in the previous section.

Besides that value, it is necessary to consider the Peak Sun Hours (PSH). This term refers to the solar insolation which a particular location would receive if the sun were shining at its maximum value for a certain number of hours. Since the peak solar radiation is 1 kW/m², the number of peak sun hours is numerically identical to the average daily solar insolation. This value depends on the irradiance that the chosen location enjoys and it can be measured by the NREL's PVWatts Calculator [10].

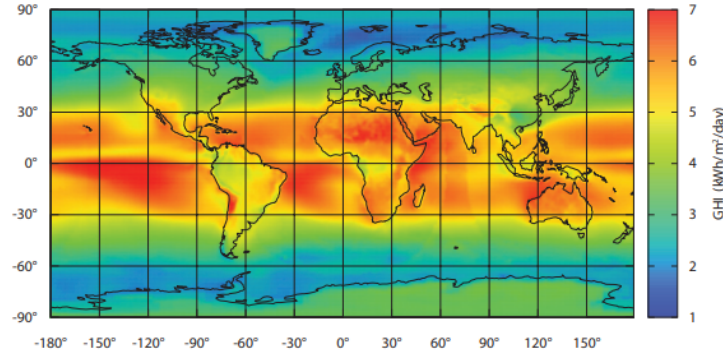


Figure 2.3: The average global horizontal irradiance of the World (PSH) [4]

It is possible to estimate the rated PV power required in the PV system, knowing the load demanded at the PV output and the PSH.

The Minimum PV Power can be obtained by dividing the total Daily Load Demand at the PV output with the equivalent sun hours.

$$\min W_p = \frac{DDT/n}{PSH} \quad (2.5)$$

Where:

- PSH=5.24; Solar Radiation=5.24 [kWh/m²/day] and Peak Sun Hours=SR/1000=5.24 [10]
- n=[0.70;0.75;0.80]; Overall system performance taking into account the Losses. This value can vary depending on the system. Some components of the PV system, such as charge regulators and batteries require energy to perform their functions. The use of energy by the system components is denoted as system energy losses. Therefore, the total energy demand, increases with 20 to 30% in order to compensate for the system losses. Three different efficiencies are taken into account.

Taking into account a particular type of PV panel and assuming that the panel would be operated at its MPP, it is feasible to find out the required number of panels as follows.

$$npvp = \frac{\min W_p}{PVPP_p} \quad (2.6)$$

Where:

- PVPP_p=25; PVPanel Power Peak [W]

2.2.3 Charge Controller Sizing

PV generation is represented by individual panels, which are all connected to the battery. To adequately model the real scenario, no MPPT (Maximum Power Point Tracking) is undertaken, but basic PWM-Charge Control of each panel.

Two different cases can be taken into account. The first case is developed considering one PWM-charge control for the whole system (Centralized). The second case is developed considering one PWM-charge control for each PV Panel (Decentralized).

In order to size the PWM-charge, it is necessary to determine the array of the system.

PV Panels Array

If the determined number of PV panels are connected in parallel, then the maximum current of the system is calculated as follows:

$$I_{max} = I_{sc} * \text{ceil}(npvp) \quad (2.7)$$

On the other hand, if the PV panels are connected in series, the maximum voltage of the system is calculated as follows:

$$V_{max} = V_{oc} * \text{ceil}(npvp); \quad (2.8)$$

It is necessary to ensure that the charge controller parameters would conform with the maximum parameters found in the different PV configurations.

The operational voltage is the battery voltage that is supported by the controller. It is also the voltage at which the DC loads would be operated at this voltage. Thus the nominal operating DC voltage of the system is dictated by the load rating as well as the battery bank. In this case it is given as 12 V.

This is not to be confused with the maximum voltage, which simply specifies the amount of maximum voltage as provided by the PV output that the charge controller can handle at the input.

Taking into account all the previous information, the following statements must be achieved in order to find the optimal size of the Charge Controller:

- $I_{max} < I_{maxCC}$ - Maximum Charge Controller Admissible Current [A]
- $V_{max} < V_{opCC}$ - Operational Charge Controller Voltage [V]
- MPPT: NO - No MPPT Required

In general, given a choice between series and parallel, series configuration is preferred to keep the current levels down, thereby minimizing the DC cable loss [4].

2.2.4 Battery Sizing

The microgrid battery storage is aggregated and represented by a single storage model. Its nominal voltage is 12 [V] with a range between 10 and 14.5 [V] based on lead-acid battery technology models. The terminals of this battery storage form the bus for all other components of the model.

The battery size is greatly affected by the days of autonomous operation expected from the system. It is advisable to repeat that in the present case, it is necessary just a couple of hours of autonomy in the day, due to the TIER Type 2 Loads. Two different cases are taken into account. The first one is sizing considering one day of autonomy, and the second case considering just four hours a day (0.16 day) in order to compare both.

The Minimum Battery Capacity is measured in [Ah]. It is calculated by multiplying the daily total DC energy requirement of the PV system including loads and system losses by the number of days of recommended reserve time.

The depth of discharge (DOD) is the depth until which the battery can be effectively used. In order to prolong the life of lead-acid batteries, which are most commonly used, it is recommended to discharge the battery maximally by 80%. If this value is decreased, also the battery lifetime is prolonged, but the system becomes more expensive. In the end, a cost evaluation has to be made in order to choose the optimal configuration [4]. It is taking into account a DOD around 60%.

- DDT=Daily Energy Demand [Wh]
- $n=[0.70;0.75;0.80]$; Overall system performance taking into account the Losses.
- DOD=0.6; Deep of Discharge. In this case the battery has a DOD of 60%.
- $V=[12;14]$ [V]. Considering two different voltages.
- $D=[0.16;1]$ Days of autonomous operation.

$$MinCBa = \frac{DDT/n}{DOD * V} * D; \quad (2.9)$$

2.2.5 Cable Sizing

The sizing of the cable is one of the most important steps in the design of a PVSHS. It can be obtained with the following equation:

$$Section = \frac{L * I}{CoCu * V * VD} \quad (2.10)$$

Where:

- CoCu=46.82; Cooper Conductivity [m/Ohm.mm2]
- L=Distance; [m]
- I=Maximum Admissible Current; [A]
- V*VD=Voltage Drop; [V]

In the previous analysis [2], the following graphic was obtained.

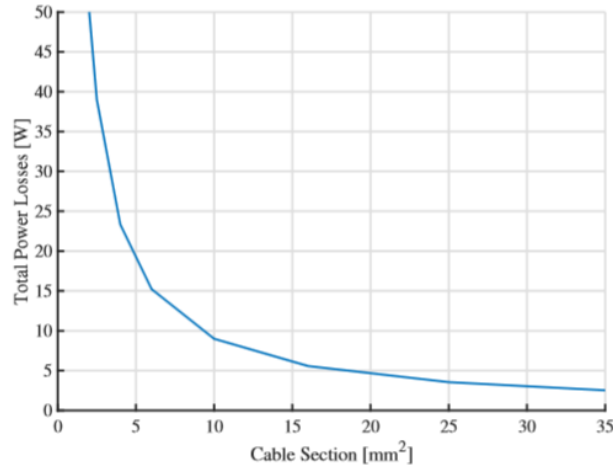


Figure 2.4: System power losses for different cable sections [2]

It can be observed that with a cable section until 4mm2, the power losses are too high. Besides, with a cable section from 15mm2, the total power losses are virtually stabilized. For this reason, the considered commercial sections will be between these values.

The following table resume the cost of the cable, considering the different possible sections: [12]:

Table 2.1: Cable Cost				
Section [mm2]	4	6	10	16
Cost [€/m]	1.2	1.5	3.00	3.30

Based on the selected section, the total cost of the cable is obtained as follows:

$$CableCost = L * Cost \quad (2.11)$$

Cable Configurations

Due to the main impact of the cable length in the final design of the PVSHS, two different cable configurations will be taking into account, in order to reduce the necessary amount of cable.

- Cable Configuration 1: In the first configuration, the battery is considered centralized. This is not the optimal case, due to the length of the cable is one of the most important items in the definition of the PVSHS. It is decisive in the total losses and in the total investment.
 - Cable Length for 6 PV Panels: 260 [m]
- Cable Configuration 2: In the second configuration, the battery is considered decentralized.
 - Cable Length for 6 PV Panels: 180 [m]

2.2.6 Power Losses

The final step for the PVSHS Sizing is the calculation of the power losses, which depends on the selected cable.

The power losses are calculated according to (2.12) and they are measured in [W].

For the analysis will be considered two different battery voltages and four different cable sections.

$$P_{losses} = \frac{(V * VD)^2}{R} \quad (2.12)$$

Where:

- $V*VD$ =Voltage Drop; [V]
- R =Cable Resistance; [Ohm]

Besides, considering the electricity tariff of Bangladesh and the hours of annual energy generation, it is possible to calculate the annual cost associated to the power losses:

$$PLCost = EAT * P_{losses} \quad (2.13)$$

Where:

- EAT =Electric Average Tariff=0.1Euro/KWh [13]
- $AP_{losses}=P_{losses}*PSH*365$
- PSH =Peak Sun Hours=5.24 [hs]

2.3 Results

2.3.1 PV Panels Sizing

The following table summarize the main results obtained:

Table 2.2: PV Panels Sizing

n	DDT	MinWp	NofPVP	PVPT	DE
0.7	357.35	97.425	4	100	366.8
0.75	357.35	90.93	4	100	393
0.8	357.35	85.247	4	100	419.2

Where:

- DDT: Daily Energy Demand [Wh/day]
- MinWp: Minimum PV Power in order to cover the demand [Wp]
- NofPVP: Number of necessary PV Panels, which indicates that four panel could be enough in order to cover the energy demand.
- PVPT: Total PV Panel Power [Wp]
- DE: Daily Total PhotoGenerated Energy [Wh/day]

The main conclusion for this step is that the minimum necessary number of PV Panels in order to cover the daily energy demand is 4 panels.

For this reason the complete analysis will be achieved taking into account 4, 5 and 6 panels, in order to evaluate the advantages and disadvantages of each option.

2.3.2 Charge Controller Sizing

The following table summarize the main results obtained:

Table 2.3: Charge Controller Sizing		
Configuration	Imax [A]	Vmax [V]
Centralized	5.8	88.8
Decentralized	1.45	22.2

Where:

- Imax: Maximum Charge Controller Admissible Current [A]
- Vmax: Maximum Operational Charge Controller Voltage [V]
- MPPT=NO - No MPPT Required

2.3.3 Battery Sizing

The following table summarize the main results obtained:

Table 2.4: Battery Sizing			
n	Voltage [V]	MinCBa1 [Ah]	MinCBa2 [Ah]
0.7	12	71	11
0.7	14	61	10
0.75	12	66	11
0.75	14	57	9
0.8	12	62	10
0.8	14	53	9

Where:

- V: Battery Voltage [V]
- MinCBa1: Minimum necessary Battery Capacity [Ah] considering D=1 (24hs).
- MinCBa2: Minimum necessary Battery Capacity [Ah] considering D=0.16 (4hs - TIER 2)

2.3.4 Cable Sizing and Power Losses Relationship

Considering all the previous results, four different Scenarios are analyzed.

- Scenario 1:
 - Cable Configuration 1
 - Vbat=12 [V]
 - Number of PV Panels: 4, 5 y 6
 - Cable Section: 4, 6, 10, 16 [mm²]
- Scenario 2:
 - Cable Configuration 1
 - Vbat=14 [V]
 - Number of PV Panels: 4, 5 y 6
 - Cable Section: 4, 6, 10, 16 [mm²]
- Scenario 3:
 - Cable Configuration 2
 - Vbat=12 [V]
 - Number of PV Panels: 4, 5 y 6
 - Cable Section: 4, 6, 10, 16 [mm²]
- Scenario 4:
 - Cable Configuration 2
 - Vbat=14 [V]
 - Number of PV Panels: 4, 5 y 6
 - Cable Section: 4, 6, 10, 16 [mm²]

- Scenario 1: RESULTS

- 4 PV Panels

Table 2.5: Scenario 1: 4 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	45.556	264	8.713
6	26.794	330	5.1247
10	14.786	660	2.8279
16	8.8577	726	1.6941

- 5 PV Panels

Table 2.6: Scenario 1: 5 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	45.074	302.4	8.6208
6	26.614	378	5.0901
10	14.725	756	2.8162
16	8.833	831.6	1.6894

- 6 PV Panels

Table 2.7: Scenario 1: 6 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	44.763	312	8.5614
6	26.543	390	5.0767
10	14.729	780	2.817
16	8.8488	858	1.6924

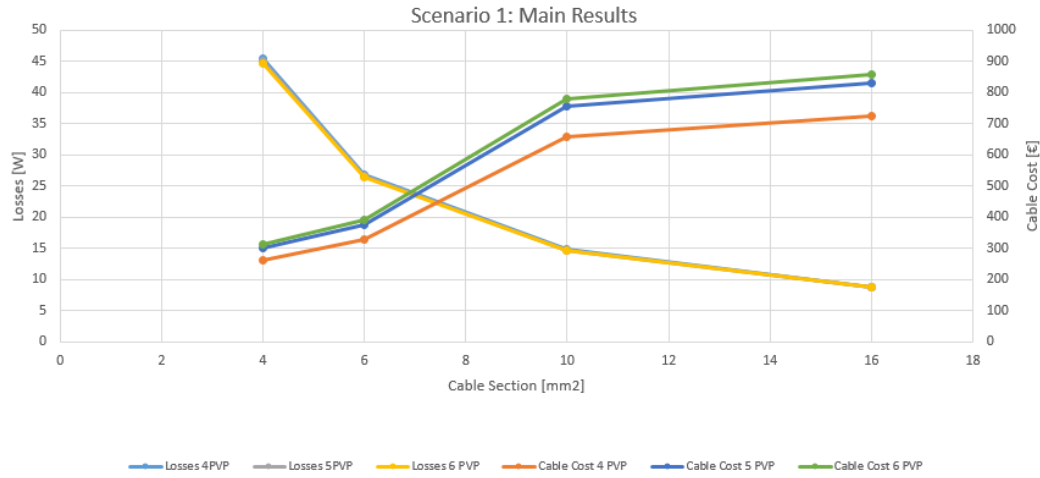


Figure 2.5: Scenario 1: Main Results

Main conclusions:

- The efficiency of the system is lower than the efficiency of traditional systems, therefore, the installation of 4 PV panels or even 5, is not enough to cover the demand. The utilization of Monocrystalline Panels can be a solution in this cases, however its expenditures are higher.
- Through the observation of the graphic, it can be said that the optimal section can be consider between 6 and 10. This is the intersection between the curves of Losses and Expenditures of the System. However, this result will be corroborated in the next chapter, through the LCOE Analysis.
- The increment in the cable section allows an improvement in the efficiency, achieving an 80% in the reduction of the losses. However, the expenditure of the cable increases about 175%.
- The annual cost of the losses is not considered in this analysis due its minimum value.

- Scenario 2: RESULTS

- 4 PV Panels

Table 2.8: Scenario 2: 4 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	29.962	264	5.7305
6	18.459	330	3.5304
10	10.47	660	2.0024
16	6.3538	726	1.2152

- 5 PV Panels

Table 2.9: Scenario 2: 5 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	29.872	302.4	5.7133
6	18.465	378	3.5315
10	10.498	756	2.0079
16	6.3795	831.6	1.2201

- 6 PV Panels

Table 2.10: Scenario 2: 6 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	29.946	312	5.7275
6	18.578	390	3.5533
10	10.591	780	2.0257
16	6.4452	858	1.2327

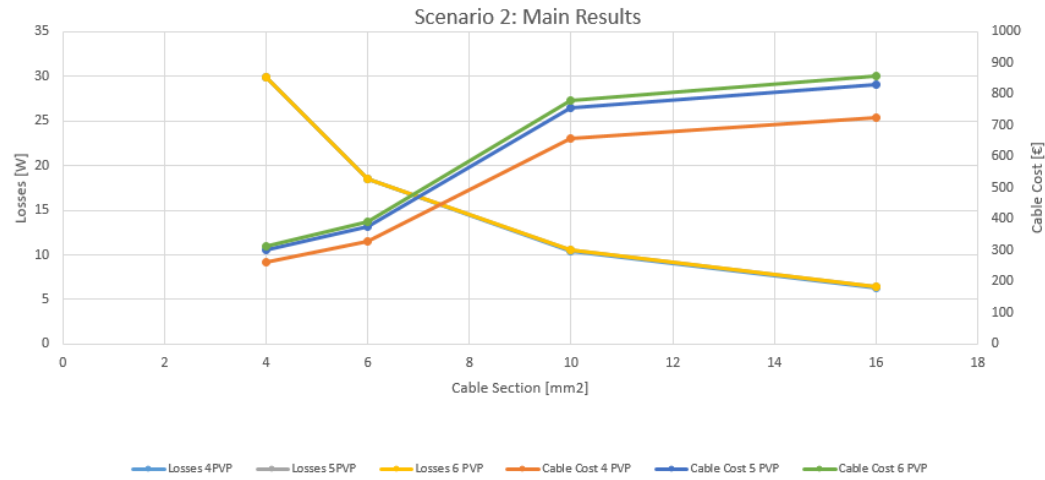


Figure 2.6: Scenario 2: Main Results

Main conclusions:

- The efficiency of the system is lower than the efficiency of traditional systems, therefore, the installation of 4 PV panels is not enough to cover the demand.
- However, the new voltage allows the installation of 5 PV Panels in order to cover the demand.
- As is the previous scenario the optimal section is between 6 and 10.
- The increment in the cable section allows an improvement of 79% in the reduction of the losses. However, the expenditure of the cable increases about 175%.
- The main improvement through the increment of the voltage is a reduction on the losses between Scenarios 1 and 2. This reduction is between 27% and 34%.

- Scenario 3: RESULTS

- 4 PV Panels

Table 2.11: Scenario 3: 4 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	36.567	192	6.9938
6	21.191	240	4.053
10	11.583	480	2.2153
16	6.9057	528	1.3208

- 5 PV Panels

Table 2.12: Scenario 3: 5 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	30.796	201.6	5.89
6	17.92	252	3.4275
10	9.8134	504	1.8769
16	5.8551	554.4	1.1198

- 6 PV Panels

Table 2.13: Scenario 3: 6 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	24.815	216	4.7462
6	14.559	270	2.7846
10	8.0051	540	1.5311
16	4.7842	594	0.91502

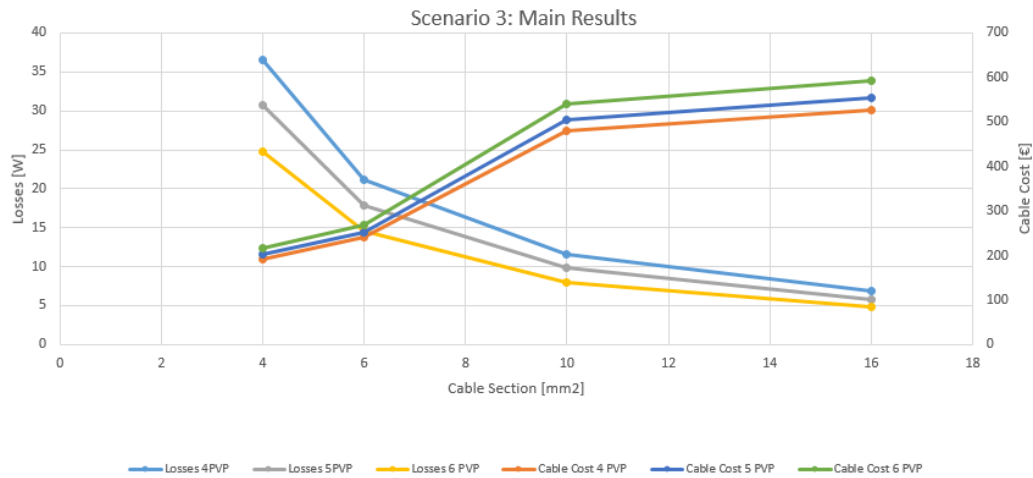


Figure 2.7: Scenario 3: Main Results

Main conclusions:

- As is the previous scenario the optimal section is between 6 and 10.
- The increment in the cable section allows an improvement of 81% in the reduction of the losses. However, the expenditure of the cable increases about 175%.
- The reduction on the losses between Scenarios 1 and 3 is differentiated by the number of PV Panels. Considering 4 PV Panels this reduction is between 19% and 22%. However, taking into account 6 PV Panels this reduction is increased between 44% and 46%.
- Furthermore, the reduction in the cable length allows to reduce the total expenditure in around 27%.

- Scenario 4: RESULTS

- 4 PV Panels

Table 2.14: Scenario 4: 4 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	22.413	192	4.2867
6	13.681	240	2.6167
10	7.7088	480	1.4744
16	4.662	528	0.89166

- 5 PV Panels - Average PV Power= [W]

Table 2.15: Scenario 4: 5 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	18.338	201.6	3.5074
6	11.223	252	2.1466
10	6.3335	504	1.2113
16	3.8329	554.4	0.73309

- 6 PV Panels

Table 2.16: Scenario 4: 6 PV Panels - Main Results

Section [mm ²]	Losses [W]	CableCost [€]	LossesCost [€]
4	14.191	216	2.7142
6	8.7332	270	1.6703
10	4.9448	540	0.94575
16	2.9973	594	0.57327

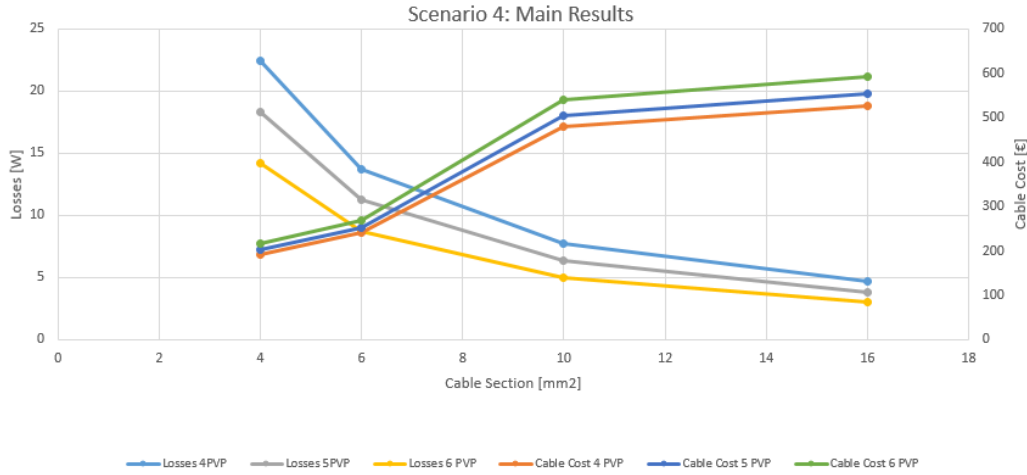


Figure 2.8: Scenario 4: Main Results

Main conclusions:

- As is all the previous scenarios the optimal section is between 6 and 10.
- The increment in the cable section allows an improvement of 79% in the reduction of the losses. However, the expenditure of the cable increases about 175%.
- The reduction on the losses between Scenarios 1 and 4 is differentiated by the number of PV Panels. Considering 4 PV Panels this reduction is between 47% and 50%. However, taking into account 6 PV Panels this reduction is increased between 66% and 68%.
- As in the previous scenario, the reduction in the cable length allows to reduce the total cable expenditure in around 27%.
- Through the comparison of the four scenarios and all the possible cable and number of PV Panels configuration it is possible to notice that the best results are obtained with the following characteristics:
 - Cable Configuration 2: 180 m
 - Number of PV Panels: 6
 - Voltage: 14 [V]
 - Cable Section: 6 [mm²] (This value will be corroborated in the following chapter).

Chapter 3

LVDC Microgrids: PVSHS LCOE

3.1 Introduction

The Levelized Cost Of Energy (LCOE) of a given technology is the ratio of lifetime costs to lifetime electricity generation, both of which are discounted back to a common year using a discount rate that reflects the average cost of capital [14].

In renewable energy technologies this value varies by technology, country and project based on the renewable energy resource, capital and operating costs, and the performance of the technology [15]. The analysis is based on discounting financial flows (annual in this case) to a common basis, taking into consideration the time value of money [6].

The PV LCOE can be calculated as follows [16]:

$$LCOE = \frac{CAPEX + \sum_{n=1}^N \frac{OPEX - RV}{(1+r)^n}}{\sum_{n=1}^N \frac{Y * (1-D)^n}{(1+r)^n}} \quad (3.1)$$

Where:

- LCOE: Levelized Cost of Energy [€/KWh]
- N: PVSHS Lifetime [years]
- CAPEX: Capital Expenditures [€/KWp]
- OPEX: Operational Expenditures [€/KWp]
- RV: Residual Value [€/KWp]
- r: Discount Rate [%]
- Y: Initial Yield [KWh/KWp]
- D: System Degradation Rate [%]

The previous equation can be expressed in the following way as well:

$$LCOE = \frac{TFC + \sum_{n=1}^N \frac{AVC}{(1+r)^n}}{\sum_{n=1}^N \frac{E*(1-D)^n}{(1+r)^n}} \quad (3.2)$$

Where:

- LCOE: Levelized Cost of Energy [€/KWh]
- N: PVSHS Lifetime [years]
- TFC: Total Fixed Costs [€]
- AVC: Annual Variable Costs [€]
- r: Discount Rate [%]
- E: Generated Energy (E=Y*PVPPp) [KWh]
- D: System Degradation Rate [%]

It is advisable to repeat that the LCOE of a given technology varies by project, and one of the main parameters in order to calculate it is the size of the project. Due to this reason, the first classification that is possible to take into account is the following:

- Utility-Scale PV: The LCOE of this type of systems is around 0.034 €/KWh (0.04 USD/KWh).
- Commercial PV: The LCOE of this type of systems is around 0.069 €/KWh (0.08 USD/KWh).
- Residential PV: The LCOE of this type of systems is around 0.095 €/KWh (0.11 USD/KWh).

The previous LCOE values were obtained from the most recent US NREL inform, and they correspond with the current solar PV costs in United states. The utilized currency in the report is the US Dollar, and for the analysis the following conversion is taking into account: 1€=1.161UDS (June, 2018) [17].

Later in this report, a comparison between the LCOE in different regions of the world will be achieve.

3.1.1 The Case of Bangladesh

The scope of the present Master Thesis is the analysis of PV Solar Home Systems (PVSHS), which are included inside the Residential classification. Notwithstanding, even inside this classification, the correspondent system expenditures can achieve a big variation, which mostly depends on the size of the system, the country, the special taxes and policies, among others. For this reason it is necessary to differentiate the LCOE analysis making a new classification inside the Residential one:

- PVSHS bigger than 1 KW
- PVSHS smaller than 1 KW

The case of the PVSHS in Bangladesh is included inside the second classification, and it is similar to the case of the PVSHS in Africa. This particular situation is described in detail in an IRENA report, which analyzes the situation of this kind of Systems in that continent [6]. The report explains the difficulty of comparing costs for PVSHS in Africa with other PVSHS benchmarks. Some of the mosts important conclusions about that report are summarized below.

- PVSHS are used by households in Africa and elsewhere to provide modern energy services but the scale, purpose and configuration of the systems all differ significantly.
- They are small systems, with typical capacities of 20 W to 100 W, that provide off-grid electricity services. In contrast, in OECD (Organization for Economic Co-operation and Development) countries small-scale solar PV rooftop systems are almost always grid-connected rooftop systems in the 1 kW to 20 kW range.
- PVSHS often deliver only DC power, with no need for an inverter but requiring an expensive battery for nighttime use. This DC system directly powers the systems electrical load, generally highly efficient LED lights and/or other small DC-powered appliances, such as radios, televisions, mobile phone charging ports and USB chargers. Solar PV rooftop systems in the OECD complement the grid by providing AC power through inverters for either self-consumption or export to the grid.
- The scales of the systems also are dramatically different. Compared to African PVSHS, some of the larger OECD rooftop solar PV systems on residential houses would seem more like utility-scale projects, with sizes thirty to thousand times larger than that of an African SPVHS. Clearly, even though these are small systems, the economies of scale of the larger OECD systems and the absence of batteries means that per watt costs will be significantly higher for the small SPVHS used in Africa.
- As a result, it is only really meaningful to compare the per watt costs of PVSHS to their direct peers, or alternatively, to calculate the cost of the energy services provided and compare that to the existing costs that Africans pay for energy services off-grid.

3.2 Methodology

Every component of the system has to be calculated through the following General Methodology, which is developed with the utilization of the MATLAB software. In the following lines, the specific assumptions of each component are explained.

In order to make an accurate analysis, besides the previous considerations, it is important to clarify that LCOE of Photo Voltaic Systems has specific characteristics: [14]

- PV has no fuel-costs.
- Lifetime for most projects ranges between 20 and 30 years, in this specific project $N=25$.
- CAPEX is concentrated during the first year.
- OPEX comprises Operation and maintenance tasks.
- $RV=0$ for the present analysis.
- $r=10\%$. This item has two principal values, 7.5% which is usually the assumption of a real cost of capital in OECD countries and China, and 10% in the rest of the world.
- Cost of capital depends on the type of PV installation and the PVSHS owner.
- The yield depends on the location and the orientation of the system.

It is necessary to clarify that the economical information of this kind of systems is obtained through two different sources, taking into account the classification mentioned in the previous section:

- PVSHS bigger than 1 KW: In this case the useful information proceed from the Reports made by national or international organizations, such as USNREL, IRENA and KICKINNO Energy. These reports represent an accurately database for systems bigger than 1KW, and it is specially useful information for PVSHS sized between 3 and 10 KW. The LCOE in these cases is around 0.095 €/KWh (0.11 USD/KWh).
- PVSHS smaller than 1 KW, In this case the useful information proceed from specific budgets, which are based on information provided by manufacturers and providers of this kind of technology. The way of calculation of these values is explained in the CAPEX section, and it is specially useful information for PVSHS sized between 10 and 100 W, but it can be used for PVSHS at least 1KW. The obtainment of the LCOE in these cases is one of the objectives of the present report.

3.2.1 Initial Data

PVSHS Technical Data

The size of the PVSHS and their principal technical features like, PV Power, losses and yield, are the main data taking into account in order to start the calculations, which is mostly obtained by [11].

It is advisable to repeat that the initial LVDC Microgrid is composed by six PV Panels, six Loads of Tier 2 Type and one battery. This configuration is modified in order to achieve some comparisons, for example between the impact of the number of PV Panels or the length of the cable in the final efficiency of the system. The main technical parameters of the system are showed below.

- PVPP: The PhotoVoltaic Panel Power delivered by all the Panels and measured in [KW]. This information is directly obtained by the solver MATLAB code.
- PVPPp: The Maximum PhotoVoltaic Panel Power delivered by all the Panels and measured in [KWp]. This information is obtained multiplying the correspondent Number of PV Panel by the PVPP of each one, which is considered as 25 Wp. The number of panels can varies between 4 and 6, in order to analyze the impact of the different arrays in the power delivered and the cost of the system.
- Losses: The system losses due to the voltage drop in each point which are measured in [KW]. This information is directly obtained by the solver MATLAB code.
- HG: The Hours of Energy Daily Generation measured in [Hs]. This is an important information, because the final value of the LCOE it is directly related with the amount of daily generation hours. This value can be measured as the Peak Sun Hours (PSH) and depends on the location. As it was said in previous sections, the microgrid location is Dhaka, Bangladesh. Then, the solar PV production is obtained based on this location considering the irradiation and temperature local conditions using NREL software PVWatts [10].
- E: The Generated Energy by the PV Panles and measured in [KWh/year].

$$E = (PVPP - Losses) * HG * 365 \quad (3.3)$$

- Y: The initial yield of the system measured in [KWh/KWp], taking into account the Power of the System, the Losses of the System and the Hours of Energy Daily Generation, and multipling the obtained value by the 365 days in order to obtain an annual value:

$$Y = \frac{(PVPP - Losses) * HG * 365}{PVPPp} \quad (3.4)$$

PVSHS Economic Data

Most of the assumptions taking into account in the following section were detailed previously:

- N: The PVP Lifetime which is expressed in [years]. Is it advisable to repeat that in this analysis it is taken as 25 years.
- RV: The Residual Value of the System expressed in [€/KWp]. For the present analysis the RV is considered as zero, however in some cases the system have a final value after its lifetime, for example, it can be sold as scrap.
- r: The Discount Rate value, which is the assumption of a real cost of capital measured in [%]. It is advisable to repeat that in this case the value is 10%.
- D: The System Degradation Rate which shows how the system loses its power generation capacity over the years, it is measured in [%] and in this case the value is 0.5%.

PVSHS Component Data

Some of the PVSHS expenditures can be dispensed in order to reduce its costs. For this reason, the objective of the present section is to determine the inclusion or not of the following items in the analysis.

In the case that the items are included, the correspondent value in the MATLAB code is 1. In the opposite case, when the items are not included, the correspondent value in the MATLAB code is 0. [Yes=1: Included or No=0;Not Included]

- INV=0 or 1; This item informs if the Inverter is included or not in the analysis. In case that the inverter is included, this has to be taken into account also in the solver.mat data.
- COM=0 or 1; Cost of Operation and Maintenance. This item can be include as an extra expenditure, however sometimes it can be achieve by the users of the system themselves, in which case it is not include in the cost analysis.

PVSHS Comparison Index

In order to obtain a methodology which can be applied in different regions around of the world, or in a year which is different than the year in which is being analyzed, different indexes can be applied.

- RCC=1; Regional Comparison Coefficient LCOE [Ad], in order to obtain a methodology which can be applied in different regions around of the world, based on the information given by the International Renewable Energy Agency (IRENA) [18].

Table 3.1: Comparison Index

North America	South America	Africa	Asia	Europe	Middle East	Oceania
1	0.92	1.58	1.33	1.42	2.25	1.42

- TCC=1; Temporal Comparison Coefficient [Ad]. Besides, it is possible to add a temporal index, because based on KIC-InnoEnergy Reports [19], PV costs will decrease about 25% from 2015 to 2030 in Rooftop Solar PV Systems, which means approximately 1.7%/year. Consequently, if the project is projected to install in the near future, it is possible to approximate a value applying a less 1.7% in the costs (In the present report the considered cost are from Dec-2017).
- ED=1.234; Currency Relationship: Euro/Dollar [Ad]. The importance if this index is due to the main data about expenditures is given in US Dollars.
- CR=101.425 (March, 2018) Currency Relationship: Local Currency/Euro [Ad]. This index is important in order to obtain the costs in the local currency. In the case of Bangladesh the currency is the Taka [TK].

3.2.2 CAPEX: Capital Expenditures

CAPEX Introduction

A Photo Voltaic (PV) System is composed of several technical components:

- The PV Panels (PVP)
- The PV Inverter(s) (I)
- The Balance of Systems (BoS): BoS refers to the components and equipment that move DC energy produced by solar panels through the rest of the system. Most often, BoS refers to all components of a PV system other than the panels and inverters. It can be differentiated into:
 - BoS Structure
 - BoS Electric

These components depend on the kind of PV system, its size, whether it is installed on a roof, integrated or ground-mounted, with or without trackers etc.

Besides these physical components it is necessary to take in consideration the Engineering and Installation Service. These are the fundamental steps in order to size and install the PV System.

With the previous data, the CAPEX value can be calculated as follows. It is measured in [€/KWp]:

$$CAPEX = PVPC + IC + BoSC + EIC \quad (3.5)$$

Where:

- PVPC: PV Panels Cost [€/KWp]
- IC: Inverter Cost [€/KWp]
- BoSC: Balance of System Cost [€/KWp]
- EIC: Engineering and Installation Cost [€/KWp]

As in the LCOE value, the CAPEX of a given technology varies by project, and one of the main parameters in order to calculate it is the size of the project. Taking into account the classification realized before:

- Utility-Scale PV: The CAPEX of this type of systems is around 830 €/KWp (1030 USD/KWp).
- Commercial PV: The CAPEX of this type of systems is around 1500 €/KWp (1850 USD/KWp).
- Residential PV: The CAPEX of this type of systems is around 2270 €/KWp (2800 USD/KWp).

The previous CAPEX values were obtained from the most recent US NREL inform, and they correspond with the current solar PV costs in United states. The utilized currency in the report is the US Dollar, and for the analysis the following conversion is taking into account: 1€=1.161UDS (June, 2018) [17].

CAPEX Methodology

The first step in order to calculate the CAPEX value, is the searching of information about real costs. It is advisable to repeat that the PVSHS can be differentiated into two types: PVSHS bigger than 1KW and PVSHS smaller than 1KW. The systems are analyzed in two different ways due to the costs between both present a big difference.

- PVSHS bigger than 1 KW:

The National Renewable Energy Laboratory (NREL) from United States, develop diverse reports every year with actualized information about the expenditures of the different components of the PV Systems [5].

It is necessary to clarify that several costs taking into account in the NREL Report are specifically for United States and they are not consider in the present analysis. The objective is to maintain a simple configuration of the PVSHS, no taking into account taxes, or some extra cost included in more complex systems. For this reason, the CAPEX value obtained in this section is lower than the final value obtained in the original report.

The original values are given in US Dollars and they have to be converter into Euros with the previous mentioned index (ED) ($1\text{€}=1.161\text{UDS}$).

It is important to explain that if the expenditure of an item does not have an specific value, but the value is between a range, an average value is calculated an considered.

- PVPanel Cost: $\text{PVPCg}=350 \text{ [USD/KWp]}$ (g=General)

- Inverter Cost: $\text{ICg}=150*\text{INV}*2 \text{ [USD/KWp]}$

This item is multiplied by 2 because of the Lifetime of the inverter. It will be necessary change one inverter during the lifetime of the whole system. The expression INV was explained before.

- Balance of System Cost (BoSCg):

 - BoS Structure Cost: $\text{BoSSg}=110 \text{ [USD/KWp]}$

 - BoS Electric Cost: $\text{BoSEg}=265 \text{ [USD/KWp]}$

 - Total BoS Cost: $\text{BoSCg}=\text{BoSSg}+\text{BoSEg} \text{ [€/KWp]}$

- Engineering and Installation Cost: $\text{EIC}=48 \text{ [USD/KWp]} = 48/\text{ED} \text{ [€/KWp]}$

This value is considered constant between both classifications of PVSHS. It is assume that in the final calculation of the LCOE, EIC value is affected by the RCC (Regional Comparison Index).

- PVSHS smaller than 1 KW:

The expenditures for this type of systems can not be founded in general reports, due to their specific applications and characteristics. In this case the useful information proceed from specific budgets, which are based on information provided by manufacturers and providers of this kind of technology [20] [21] [22].

With this information it is possible to obtain an average value of the expenditure for each of the main components of the system. These expenditures are much bigger than the obtained in the previous case.

- PVPanel Cost: $PVPCb=1900 \text{ [€/KWp]}$ (b=Bangladesh)

This expenditure is calculated based on the average cost of different PV Panels provided by different manufacturers, and divided by the PV Power correspondent of each one.

Polycrystalline PV Panels are considered. Although Monocrystalline PV Panels are more efficient, there are a large difference in the costs between both types. Considering that the system is expected to be economic, the first option is considered.

It is important to notice that the CAPEX of this PV Panels is much higher than the PV Panels bigger than 1 KW.

In some cases it is possible to obtain a smaller expenditure value, but it is necessary to purchase a large number of PV Panels, for example over than one thousand. This situations are not considered due to the mentioned characteristics of these small microgrids.

- Inverter Cost: $ICb=430*INV*2 \text{ [€/KWp]}$

This expenditure is calculated based on the average value of different Inverters provided by different manufacturers, and divided by the PV Power supported by each one. This item is multiplied by 2 because of the Lifetime of the inverter, it will be necessary change one inverter during the lifetime of the whole system. The expression INV was explained before.

- Balance of System Cost (BoSCb):

BoS Structure Cost (BoSSb)

Mounting Structures Cost: $MSCb=110 \text{ [USD/KWp]} = 110/ED \text{ [€/KWp]}$

The CAPEX value of this item is specially difficult to calculate, due its value depends more on the size [m²] than the power [KWp] of the PV Panels. For this reason, different structures for one, two or three panels has basically the same costs and it is no meaningful to calculate the value based on budgets. Due to this situation, this value is considered the same than in the case of PV Panels bigger than 1 KWp.

BoS Electric Cost (BoSEb):

Battery Cost: $BCb=160*3*HG \text{ [€/KWp]}$.

The value obtained through the different budgets is 160 [€/KWh]. It is obtained after dividing the commercial price of different provider by the product of the Battery Capacity [Ah] by the Battery Voltage [V].

Then it is necessary to multiply the previous value by the Peak Sun Hours (HG) in order to obtain a value measured in [€/KWp].

This item is multiplied by 3 because of the Lifetime of the battery. It will be necessary change three batteries during the lifetime of the whole system. This value depends on the use and the DOD of the battery.

Charge Controller Cost (PWMC): $ChCCb=200$ [€/KWp]

This expenditure is calculated based on the average value of different Charge Controllers provided by different manufacturers, and divided by the PV Power supported by each one.

Cable Cost: $cablecost=(cableprice*cablelength)$ [€]

Cable Cost based on CAPEX: $cableCAPEX=(cableprice*cablelength)/PVPPp$ [€/KWp]

It is advisable to repeat that the Price of the Cable is considered as follows:

Table 3.2: Cable Cost				
Section [mm ²]	4	6	10	16
Cost [€/m]	1.2	1.5	3.00	3.30

Total BoS Cost: $BoSC=BoSS+BoSE$ [€/KWp]

– Engineering and Installation Cost: $EIC=48$ [USD/KWp] = $48/ED$ [€/KWp]

All the previous values are the base data utilized to calculate the CAPEX Value, as it is shown in (3.5).

Finally, it is advisable to calculate the Initial Investment of the system. CAPEX value is measured in [€/KWp], but if it is necessary to know the initial investment of the system, it is possible to obtain the Total Fixed Costs measured in [€].

$$TFC = CAPEX * PVPPp \quad (3.6)$$

If the project is projected outside of Europe, the Fixed Costs can be calculated in the local currency (CR). In this case the local currency of Bangladesh is the Taka [TK] (1€=97.44TK) (June, 2018) [23].

$$TFC_{lc} = TFC * CR \quad (3.7)$$

3.2.3 OPEX: Operational Expenditures

OPEX Introduction

The OPEX value includes the costs of Operation and Maintenance of the installation. Residential PV systems are characterized by very low operating costs, which usually comprise just a few hours per year of regular maintenance of the modules.

- Operational Costs
- Maintenance Costs

The previous values are integrated in only one expression: OM, which is the base of the OPEX value calculation. The OPEX is calculated as follows and it is measured in [€/KWp/year].

$$OPEX = OMC * COM \quad (3.8)$$

Where:

- OMC: Operation and Maintenance Costs measured in [€/KWp/year]
- COM: Cost of Operation and Maintenance. In some cases this labor can be included as an extra cost, but in the other hand, the labor can be achieved by the users of the system. In this last case, the expenditure is not taking into account [Yes=1 or No=0]

OPEX Methodology

This case is simpler than CAPEX, because the only one expenditure that it is necessary to take into account is the Operation and Maintenance [5]. This value depends on the region, and on the size of the system among others. It is considered constant between both classifications of PVSHS, and it is assume that in the final calculation of the LCOE, this value is affected by the RCC (Regional Comparison Index).

- Operational and Maintenance Costs: $OMC=21 \text{ [USD/KWp/year]} = 21/ED \text{ [€/KWp/year]}$

Like in the case of the CAPEX, it is possible to obtain a new value in order to know the Operational and Maintenance Annual Cost of the system in [€].

$$OMAC = OPEX * PVPPp \quad (3.9)$$

If the project is projected outside of Europe, the Fixed Costs can be calculated in the local currency (CR). In this case the local currency of Bangladesh is the Taka [TK] (1€=97.44TK) (June, 2018)

$$OMAClc = OMAC * CR \quad (3.10)$$

3.2.4 Annual Variable Costs

The Annual Variable Costs are composed by the OPEX Value and the Residual Value of the System. It is measured in [€/KWp/year]. It is important to repeat that in the present case the RV is considered as zero.

$$AVC = \sum_{n=1}^N = \frac{OPEX - RV}{(1 + r)^n} \quad (3.11)$$

Where:

- OPEX: Operational Expenditures [€/KWp/year]
- RV: Residual Value [€/KWp/year]
- r: Discount Rate [%]
- n: PV System Lifetime [years]

Another important value is the Annual Variable Costs measured in [€/year]. This value is obtained by (3.12) but considering the OMAC value instead the OPEX value. Besides, in case that the RV is considered, it is necessary to obtain this value in [€] instead [€/KWp].

$$AVC = \sum_{n=1}^N = \frac{OMAC - RV}{(1 + r)^n} \quad (3.12)$$

Where:

- OMAC: Operational and Maintenance Annual Costs [€/year]
- RV: Residual Value [€/year]
- r: Discount Rate [%]
- n: PV System Lifetime [years]

3.2.5 Annual Generated Energy

The Annual Generated Energy is measured in [KWh/KWp/year]. This value is calculated taking into account the initial Yield of the system, the System Degradation Rate and the Discount Rate, and considering the PVSHS Lifetime.

$$AGE = \sum_{n=1}^N = \frac{Y * (1 - D)^n}{(1 + r)^n} \quad (3.13)$$

Where:

- Y: Initial Yield [KWh/KWp/year]
- D: System Degradation Rate [%]
- n: PV System Lifetime [years]
- r: Discount Rate [%]

Another important value is the Annual Generated Energy measured in [KWh/year]. This value is obtained by (3.12) but considering the OMAC value instead the OPEX value. Besides, in case that the RV is considered, it is necessary to obtain this value in [€] instead [€/KWp].

$$AGE = \sum_{n=1}^N = \frac{E * (1 - D)^n}{(1 + r)^n} \quad (3.14)$$

Where:

- E: Generated Energy [KWh/year]
- D: System Degradation Rate [%]
- n: PV System Lifetime [years]
- r: Discount Rate [%]

3.2.6 Summary of the Methodology

The following tables are developed in order to summarize all the previous concepts.

Table 3.3: CAPEX and TFC Summary

CAPEX [€/KWp]	TFC [€]
CAPEX = PVPC + IC + BoSC + EIC	TFC = CAPEX x PVPPp
CAPEX: Capital Expenditures	TFC: Total Fixed Costs
PVPC: PVPanel Cost	CAPEX: Capital Expenditures
IC: Inverter Cost	PVPPp: PV Panel Power Peak
BoSC: Balance of System Cost	
EIC: Engineering and Installation Cost	

Table 3.4: OPEX, OMAC and AVC Summary

OPEX [€/KWp]	OMAC [€]	AVC [€]
OPEX = OMC x COM	OMAC = OPEX x PVPPp	AVC=(OMAC-RV)/(1+r) ⁿ
OPEX: Operational Expenditures	OMAC: Operational and Maintenance Annual Cost	AVC: Annual Variable Cost
OMC: Operational and Maintenance Costs	OPEX: Operational Expenditures	OMAC: Operational and Maintenance Annual Cost
COM: Cost of Operation and Maintenance	PVPPp: PV Panel Power Peak	RV: Residual Value
		r: Discount Rate
		n: PV System Lifetime

Table 3.5: Generated Energy Summary

Y [KWh/KWp]	E [KWh]	AGE [KWh]
Y=((PVPP-Losses) x HG x 365) / PVPPp	E = Y x PVPPp	AGE=(E x (1 - D)) ⁿ /(1 + r) ⁿ
Y: Initial Yield	E: Generated Energy	AGE: Annual Generated Energy
PVPP: PV Panel Power	Y: Initial Yield	E: Generated Energy
HG: Equivalent to Peak Sun Hours (PSH)	PVPP: PV Panel Power Peak	D: Degradation Rate
PVPP: PV Panel Power Peak		n: PV System Lifetime
		r: Discount Rate

3.3 Results

Considering all the previous results, four different Scenarios are analyzed.

- Scenario 1:
 - Cable Configuration 1
 - Vbat=12 [V]
 - Number of PV Panels: 4, 5 y 6
 - Cable Section: 4, 6, 10, 16 [mm^2]
- Scenario 2:
 - Cable Configuration 1
 - Vbat=14 [V]
 - Number of PV Panels: 4, 5 y 6
 - Cable Section: 4, 6, 10, 16 [mm^2]
- Scenario 3:
 - Cable Configuration 2
 - Vbat=12 [V]
 - Number of PV Panels: 4, 5 y 6
 - Cable Section: 4, 6, 10, 16 [mm^2]
- Scenario 4:
 - Cable Configuration 2
 - Vbat=14 [V]
 - Number of PV Panels: 4, 5 y 6
 - Cable Section: 4, 6, 10, 16 [mm^2]

- Scenario 1: LCOE RESULTS

- 4 PV Panels

Table 3.6: Scenario 1: 4 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	7391.3	0	1.9569
6	8051.3	0	1.154
10	11351	0	1.2581
16	12011	0	1.1973

- 5 PV Panels

Table 3.7: Scenario 1: 5 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	7170.5	0	1.3132
6	7775.3	0	0.97671
10	10799	0	1.1292
16	11404	0	1.1013

- 6 PV Panels

Table 3.8: Scenario 1: 6 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	6831.3	0	1.0379
6	7351.3	0	0.85318
10	9951.3	0	1.0027
16	10471	0	0.99059

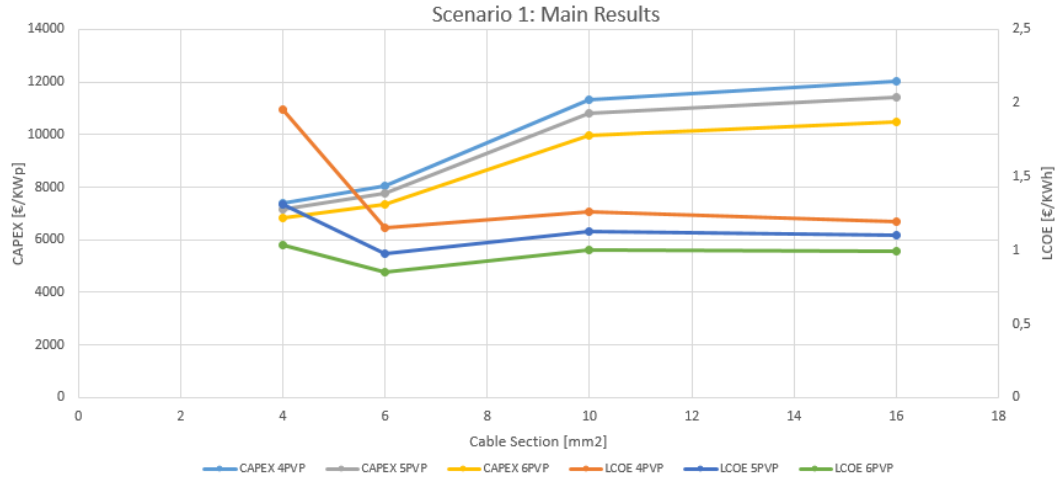


Figure 3.1: Scenario 1: LCOE Main Results

Main conclusions:

- The section and length of the cable are two crucial values in determining the optimum configuration of the PVSHS.
- Although the section that generates fewer losses is 16 mm^2 , the high final cost of the system does not compensate this loss reduction.
- In the technical model the optimal section was considered between 6 and 10. In this model, it is possible to assert that the optimal section for all the cases is 6 mm^2 . It is clear to observe that this result is obtained with the lower LCOE for all the considered cases.
- CAPEX value increases with the section of the cable. However, due to the amount of losses and the final photogenerated energy, this value decreases with the number of PV Panels. For this reason notwithstanding the initial investment will be increased, the expenditure by kWp will be more convenient.

- Scenario 2: LCOE RESULTS

- 4 PV Panels

Table 3.9: Scenario 2: 4 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	7391.3	0	0.88688
6	8051.3	0	0.78265
10	11351	0	0.97513
16	12011	0	0.97359

- 5 PV Panels

Table 3.10: Scenario 2: 5 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	7170.5	0	0.75953
6	7775.3	0	0.70907
10	10799	0	0.89813
16	11404	0	0.9073

- 6 PV Panels

Table 3.11: Scenario 2: 6 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	6831.3	0	0.67125
6	7351.3	0	0.6439
10	9951.3	0	0.81041
16	10471	0	0.82296

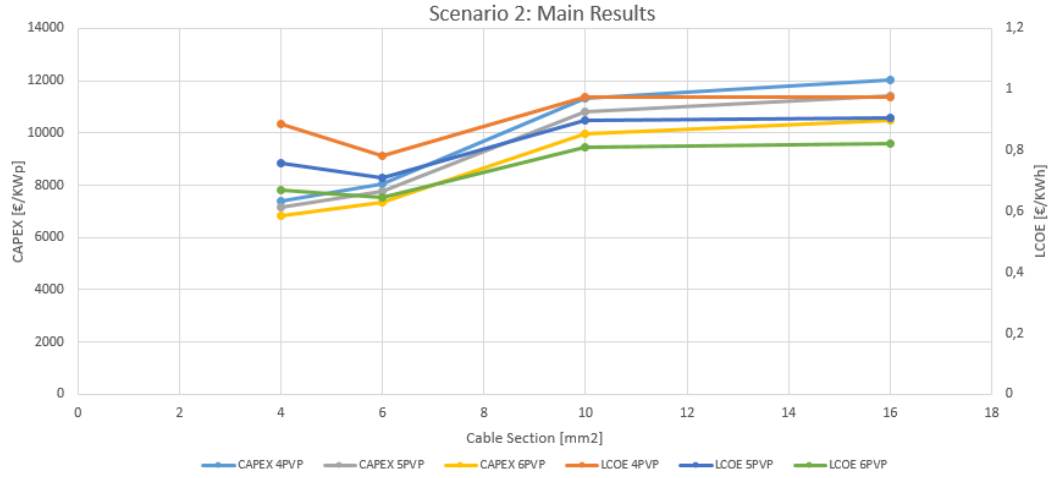


Figure 3.2: Scenario 2: LCOE Main Results

Main conclusions:

- All the previous conclusions are applicable in the present scenario:
 - The section and length of the cable are two crucial values in determining the optimum configuration of the PVSHS.
 - Although the section that generates fewer losses is 16 mm^2 , the high final cost of the system does not compensate this loss reduction.
 - In the technical model the optimal section was considered between 6 and 10. In this model, it is possible to assert that the optimal section for all the cases is 6 mm^2 . It is clear to observe that this result is obtained with the lower LCOE for all the considered cases.
 - CAPEX value increases with the section of the cable. However, due to the amount of losses and the final photogenerated energy, this value decreases with the number of PV Panels. For this reason notwithstanding the initial investment will be increased, the expenditure by KWp will be more convenient.
- Additionally it is important to notice that the LCOE between scenario 1 and 2 it is reduced in around 24%.
- CAPEX value is the same between both scenarios.

- Scenario 3: LCOE RESULTS

- 4 PV Panels

Table 3.12: Scenario 3: 4 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	6671.3	0	1.5023
6	7151.3	0	0.96826
10	9551.3	0	1.0322
16	10031	0	0.98624

- 5 PV Panels

Table 3.13: Scenario 3: 5 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	6364.1	0	0.99002
6	6767.3	0	0.79366
10	8783.3	0	0.88949
16	9186.5	0	0.87151

- 6 PV Panels

Table 3.14: Scenario 3: 6 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	6191.3	0	0.79492
6	6551.3	0	0.70407
10	8351.3	0	0.81103
16	8711.3	0	0.80718

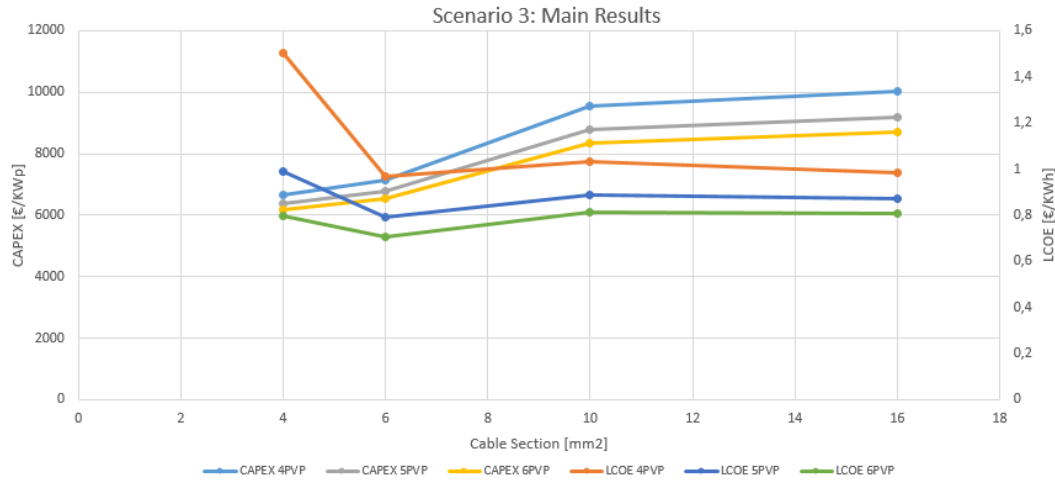


Figure 3.3: Scenario 3: LCOE Main Results

Main conclusions:

- All the previous conclusions are applicable in the present scenario:
 - The section and length of the cable are two crucial values in determining the optimum configuration of the PVSHS.
 - Although the section that generates fewer losses is 16 mm^2 , the high final cost of the system does not compensate this loss reduction.
 - In the technical model the optimal section was considered between 6 and 10. In this model, it is possible to assert that the optimal section for all the cases is 6 mm^2 . It is clear to observe that this result is obtained with the lower LCOE for all the considered cases.
 - CAPEX value increases with the section of the cable. However, due to the amount of losses and the final photogenerated energy, this value decreases with the number of PV Panels. For this reason notwithstanding the initial investment will be increased, the expenditure by KWp will be more convenient.
- Additionally it is important to notice that the LCOE between the scenario 1 and 3 it is reduced in around 17%.
- CAPEX value is around 11% lower than in the scenarios 1 and 2.

- Scenario 4: LCOE RESULTS

- 4 PV Panels

Table 3.15: Scenario 4: 4 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	6671.3	0	0.74693
6	7151.3	0	0.67085
10	9551.3	0	0.80574
16	10031	0	0.80463

- 5 PV Panels

Table 3.16: Scenario 4: 5 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	6364.1	0	0.62153
6	6767.3	0	0.5908
10	8783.3	0	0.71406
16	9186.5	0	0.72126

- 6 PV Panels

Table 3.17: Scenario 4: 6 PV Panels - LCOE Results

Section [mm ²]	CAPEX [€/KW _p]	OPEX [€/KW _p]	LCOE [€/KWh]
4	6191.3	0	0.55609
6	6551.3	0	0.54609
10	8351.3	0	0.66255
16	8711.3	0	0.67423

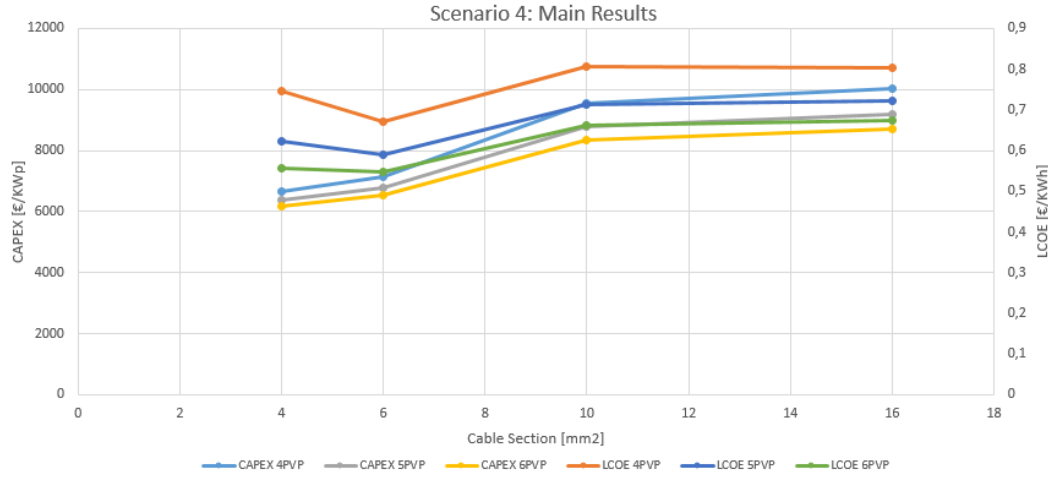


Figure 3.4: Scenario 4: LCOE Main Results

Main conclusions:

- All the previous conclusions are applicable in the present scenario:
 - The section and length of the cable are two crucial values in determining the optimum configuration of the PVSHS.
 - Although the section that generates fewer losses is 16 mm^2 , the high final cost of the system does not compensate this loss reduction.
 - In the technical model the optimal section was considered between 6 and 10. In this model, it is possible to assert that the optimal section for all the cases is 6 mm^2 . It is clear to observe that this result is obtained with the lower LCOE for all the considered cases.
 - CAPEX value increases with the section of the cable. However, due to the amount of losses and the final photogenerated energy, this value decreases with the number of PV Panels. For this reason notwithstanding the initial investment will be increased, the expenditure by kWp will be more convenient.
- Additionally it is important to notice that the LCOE between scenario 1 and 4 it is reduced in around 36%.
- CAPEX value is around 11% lower than in the previous scenarios.
- Through the comparison of the four scenarios and all the possible cable and number of PV Panels configuration it is possible to corroborate that the best results are obtained with the following characteristics:
 - Cable Configuration 2: 180 m
 - Number of PV Panels: 6
 - Voltage: 14 V
 - Cable Section: 6 mm^2

The data expressed in the following figure can be used as a comparison, in order to obtain some conclusions about the presented values. The following data represent the LCOE values in a Rooftop Solar PV Residential Systems in United States.

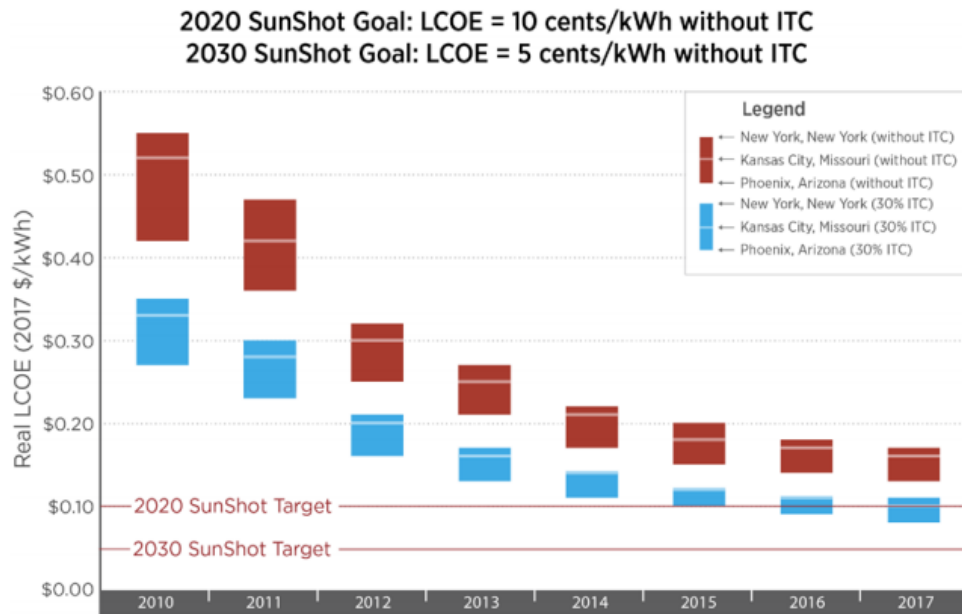


Figure 3.5: LCOE of Residential PVPS in US [5]

The comparison between both values allows to develop some conclusions:

- The extremely high LCOE costs in Bangladesh implies in one hand the high CAPEX values of this kind of systems, and in the other hand the very low power generated (almost thirty times lower) among other reasons.
- It is advisable to repeat that is not meaningful to compare the costs of the two systems, as the results would be very misleading. The scale, purpose and configuration of the systems all differ significantly. For this reason it was necessary to carry out a deeper analysis, which was done in this chapter.

Chapter 4

Master's Thesis Budget

The present chapter aim to calculate the expenditures associated with the development of this Master's Thesis.

Two main expenditures are taken into account:

- Engineering Expenditures: It is concentrated especially on hours of work of the author from the beginning of the idea until the development of this document.
- Software and Hardware Expenditures: Laptop, software license, and news subscription complete the list of costs.

4.1 Labor Expenditures

The following table details the labor cost of the study, which basically includes the engineering costs incurred in the realization of the present project.

Table 4.1: Labor Expenditures

Item	Wage [€/h]	Hours [h]	Total Expenditures [€]
1.Master's Thesis Definition	20	50	1000
2. LVDC Microgrids Research	20	150	3000
3. LVDC Sizing Development	20	300	6000
4. LVDC LCOE Development	20	300	6000
5. Revision, Results and Conclusions	20	100	2000
TOTAL		900	18000

4.2 Material Expenditures

The following table presents the cost of the materials utilized in order to develop the complete study.

Table 4.2: Material Expenditures

Item	Price [€/un]	Units [ad]	Total Expenditures [€]
Laptop	500	1	500
MATLAB Software	80	1	80
OVERLEAF Software	0	1	0
TOTAL			580

4.3 Total Budget

The following table summarizes the total budget of the study, considering the labor and the material expenditures.

Table 4.3: Total Expenditures

Item	Total Expenditure [€]
Labor Expenditures	18000
Material Expenditures	580
TOTAL	18580

Chapter 5

Environmental Impact

Renewable energy has a key role to play in the decarbonisation of the energy sector and the resulting mitigation of climate change effects. To better illustrate the potential impact of renewable energy, IRENA has developed a tool to estimate the greenhouse gas emissions avoided each year as a result of renewable energy deployment in a country [24].

It is possible to calculate the total amount of emissions avoided by the PV Generation in Bangladesh:

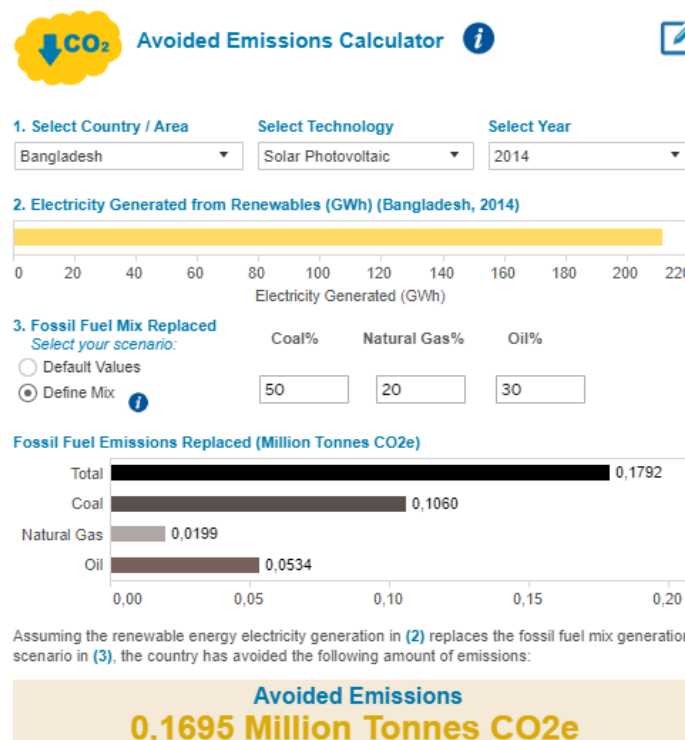


Figure 5.1: Avoided Emissions

Considering the previous value, it is possible to calculate the amount of CO₂ avoided by every KWh of Photogenerated Energy [KTnCO₂/KWh].

Then it is feasible to calculate the amount of GHG for year of generation of the project.

- Number of PV Panels: 6
- Cable Section: 6 mm²
- Battery Voltage: 14 V
- Cable Length: 180 m

Table 5.1: Avoided Emissions in the Country

Avoided Emission [Tn CO ₂ e]	Electricity Generated [Wh]	[TnCO ₂ /Wh]
0.1695x10 ⁶	211.8x10 ⁹	8.0028x10 ⁻⁷

Table 5.2: Avoided Emissions by the Project

[TnCO ₂ /Wh]	Electricity Generated [Wh]	[TnCO ₂]
8.0028x10 ⁻⁷	206730	0.1654

Beyond this values, contemporary efforts to reduce greenhouse gas emissions including CO₂, SO_x, and NO_x, provide a cleaner environment for off-grid communities. Expanding the capacity of non-carbon generation technologies and energy storage would reduce the reliance on conventional generation technologies and facilitate achieving this objective [1].

Conclusions

The purpose of the present Master's Thesis was the development of an integral model for the sizing and costing of Low Voltage Direct Current (LVDC) Electrical Microgrids, based on Renewable Energy (RENE) Technology.

The main objective in the development of the models is to find an optimal configuration for the PVSHS, achieving a balance between the technical and the economical characteristics of the microgrid.

The principal results obtained in the Sizing Methodology, were in terms of the number of PV Panels and the section and the length of Cable utilized. Due to the little amount of energy necessary to cover the demand, it will be possible to use a minor number of PV Panels than the consider in previous studies, 4 or 5 instead 6. However, the possibility of installing just 4 PV Panels is only possible with more efficient PV Panels.

Besides that, the section and length of the cable are two crucial values in the determination of the optimum configuration of the PVSHS. For this reason, two different cable configurations and four distinct cable sections were analyzed. Although the larger section generates fewer losses, the high final cost of the system does not compensate this loss reduction. In the technical model the optimal section was considered between 6 and 10. But in the economical model, it was possible to assert that the optimal section for all the cases is 6 mm^2 .

In terms of the Economical Analysis the analysis was divided into PVSHS bigger than 1KW and smaller than 1KW. The main result obtained is related with the LCOE value and the inputs utilized in order to calculated it. A new LCOE model was developed for microgrids smaller than 1KW, due to the correspondent expenditures can not be obtained from general reports.

Additionally, CAPEX value increases with the section of the cable. However, due to the amount of losses and the final photogenerated energy, this value decreases with the number of PV Panels. For this reason notwithstanding the initial investment will be increased, the expenditure by KWp will be more convenient.

It is advisable to repeat that is not meaningful to compare the costs of the two types of Residential PVSHS, as the results would be very misleading. The scale, purpose and configuration of the systems all differ significantly.

Finally, it is important to conclude that the extremely high LCOE costs in Bangladesh implies in one hand the high CAPEX values of this kind of systems, and in the other hand the very low power generated (almost thirty times lower) among other reasons.

Acknowledgements

I want to thank Oriol, for allowing me to be part of this wonderful project, and for his guidance and support throughout these months of work.

I also want to thank Edu for sharing me tools and for giving me some advices.

Besides, I especially want to thank my two partners, Edu and Raimon. They are the best partners that I could have for this project. Thank you for all the support.

Finally, I want to thank my family and friends, who accompanied me throughout this beautiful process.

Appendix A

solver.m - MATLAB Code

```
%% Inputs
Vbat = 12;           % Volts
Tc = 25.15;          % C
G = 1000;             % W/m^2
Pload = -50;
MaxVload = 15;
converter = 'no';

npv = 6; % number of PV cells
load('distances.mat'); % Matrix with distances between nodes
load('type.mat');      % Vector specifying pv(1), load(-1), battery(0)
pvnumber;

% IMPORTANT: multiply by 2 the cable resistance (representing the
% 2-side resistances of the circuit)
section = 4;          % mm^2
rho_Cu = 0.0171;      % [Ohmm^2/m]
r = 2*rho_Cu/section; % Ohms/m

if length(dist) ~= length(type)
    disp('dist and type should have the same length')
    return
end

%% General parameters
initialization

%% PV panel
[Pmax, fig] = pvcurve(G, Tc);

%% Circuit definition
nNodes = length(type);
indexBat = find(~type);
indexPV = find(type == 1);
indexLoad = find(type == -1);
```

```

[Y, R] = admittance(dist, r);

%% Solve system
i=1;
switch(converter)
    case('all_config')
        title('PV_annel');
        converter = 'no'; solver; title('Without_converters')
        converter = 'bat'; solver; title('Battery_converter')
        converter = 'pv'; solver; title('PV_converters')
        converter = 'all'; solver; title('Battery_and_PV_converters')
        converter = 'all_config';
    case('all') % Converters in both PVs and batteries
        Vbat = MaxVload-1;
        iteration;
        precision = 0.01;
        while prod(Vsource(indexLoad) < MaxVload)
            Vbat = Vbat + precision;
            iteration;
        end
        Vbat = Vbat - precision;
        iteration;
    case('bat') % Converters only in batteries
        if G > 20
            optimizeVbat;
            precision = 0.01;
            while sum(Vsource(indexLoad) > MaxVload)
                Vbat = Vbat - precision;
                iteration;
            end
        else
            Vbat = MaxVload-1;
            iteration;
            precision = 0.01;
            while prod(Vsource(indexLoad) < MaxVload)
                Vbat = Vbat + precision;
                iteration;
            end
            Vbat = Vbat - precision;
            iteration;
        end
    case{'no', 'pv'} % No converters and Converters only in PVs
        iteration
    otherwise
        error('converter_should_be_"no",_"all",_"bat",_"pv"_"or_"all_config')
end
Isource(indexBat) = (Vbat'-Vnode(indexBat))./diag(indexBat);
Ibat = Isource(indexBat);
% Get current & voltage vectors for each type of source
Vpv = Vsource(indexPV); Ipv = Isource(indexPV);
VL = Vsource(indexLoad); IL = Isource(indexLoad);

```

%% Plot operating points

legend_text = 'I-V_{curve}';

```
for i = 1:length(Vpv)
    subplot(2,1,1)
    plot([Vpv(i) Vpv(i)],[0 Ipv(i)], 'Marker', '*','LineWidth',2)
    subplot(2,1,2)
    plot([Vpv(i) Vpv(i)],[0 Vpv(i)*Ipv(i)], 'Marker', '*','LineWidth',2)
```

legend_text = cat(1,legend_text,{strcat('PV',num2str(i))});

end

```
set(gca, 'LineWidth',2, 'Fontname', 'times', 'FontSize',16)
legend(legend_text, 'Location', 'west')
xlabel('Voltage[V]'); ylabel('Power[W]')
subplot(2,1,1)
set(gca, 'LineWidth',2, 'Fontname', 'times', 'FontSize',16)
legend(legend_text, 'Location', 'west')
xlabel('Voltage[V]'); ylabel('Current[A]')
```

%% Losses

Plosses = zeros(size(R));

```
for i = 1:length(R)
    Plosses(i,i) = (Vsource(i)-Vnode(i))^2 / R(i,i);
    for j = i+1:length(R)
        Plosses(i,j) = (Vnode(i)-Vnode(j))^2/R(i,j);
    end
end
```

end

Losses = sum(sum(Plosses));

%% Voltage Drops from Battery node (3)

dV = zeros(length(R),2);

```
for i = 1:length(R)
    dV(i,1) = Vnode(indexBat) - Vnode(i); % Column 1: absolute Voltage drop
    dV(i,2) = dV(i,1)/Vnode(indexBat) * 100; % Column 2: drop percentage
end
```

end

%% Table data

rows = {};

iPV = 0; iBat = 0; iLoad = 0;

powerPV = 0; powerLoad = 0; powerBat = 0;

Powers = Vsource.*Isource;

for i = 1:length(Isource)

switch type(i)

case 1

iPV = iPV +1;

rows = cat(1,rows,{strcat('PV',num2str(iPV))});

powerPV = powerPV + Powers(i);

case 0

iBat = iBat +1;

```

        rows = cat(1,rows,{ strcat( 'Bat ',num2str(iBat))});
        powerBat = powerBat + Powers(i);
    case -1
        iLoad = iLoad +1;
        rows = cat(1,rows,{ strcat( 'Load ',num2str(iLoad))});
        powerLoad = powerLoad + Powers(i);
    end
end
data = table((1:nNodes)',Vsource,Isource,Powers);
data.Properties.RowNames = rows;
data.Properties.VariableNames = {'Node' 'Voltage' 'Current' 'Power'};

%% Data for the article
summary = table([powerPV;powerLoad;Pbat;0;0;0],[mean(Vpv.*Ipv);mean(VL.*IL);...
    mean(Vbat.*Ibat);max(abs(dV(:,2)));max(abs(Isource));Losses]);
summary.Properties.RowNames = {'PV_power'; 'Load_Power'; 'Battery_Power';...
    'Voltage_drop'; 'Max_Current'; 'Total_Losses'};
summary.Properties.VariableNames = {'Sum' 'Mean'}

%% Total distance

distance = 2*sum(sum(triu(dist)))

%% Print commands
% set(gcf,'PaperPositionMode','auto')
% print -depsc -r600 ./plot.eps

```

Appendix B

LVDC Microgrids: PVSHS Sizing - MATLAB Code

```
%% LVDC Microgrids: PVSHS Sizing
```

```
solver;  
sum(Powers(indexPV));  
sum(sum(Plosses));  
cablelength=distance;  
cablesection=section;  
npv;
```

```
%% ENERGY DEMAND
```

```
%LOADS from EXCEL
```

```
LOADS=xlsread('CARGAS');  
Hour=xlsread('CARGAS','Tabelle1_(2)','B2:B139'); %W  
Load=xlsread('CARGAS','Tabelle1_(2)','E2:E139'); %W
```

```
X=Hour;  
Y=Load;  
plot(X,Y)
```

```
%Daily Energy Demand
```

```
DD=trapz(X,Y); %One House [Wh/day]  
DDT=DD*6; %Six Houses [Wh/day]
```

```
%Annual Energy Demand
```

```
AD=DD*365; %One House [Wh/day]  
ADT=DDT*365; %Six Houses [Wh/year]
```

```
%% PV Panels Sizing
```

```
PSH=5.24; %Solar Radiation=5.24 [kWh/m2/day] & Peak Sun Hours=SR/1000=5.24
```

```

PVP=25; %PVPanel Power [W]
Isc=1.45; %Short Circuit Current [A]
Voc=22.2; %Open Circuit Voltage [V]
n=0.75; %Performance of the System

minWp=(DDT/n)/(PSH); %Minimum PVP Wp [Wp]
npvp=minWp/PVP; %Number of Panels [Ad]

PVPT=PVP*ceil(npvp); %PVPanel Power for all of the Panels [Wp]
DE=PVPT*5.24*n; %Daily Energy Generated by the PVPanels [Wh/day]
AEi=DE*365; %Annual Energy Generated by the PVPanels [Wh/year]

ResultsPVP=[DDT' minWp' ceil(npvp)' PVPT' DE'];

%% CHARGE CONTROLLER Sizing

%Imax<ImaxCC - Maximum Charge Controller Admisible Current [A]
%Vmax<VopCC - %Operational Charge Controller Voltage [V]
%MPPT=NO - No MPPT Required

%Centralized Charge Controller
Imax1=Isc*ceil(npvp); %Paralel Configuration PVP
Vmax1=Voc*ceil(npvp); %Serie Configuration PVP

%One Charge Controller for each PV Panel
Imax2=Isc;
Vmax2=Voc;

ResultsChC=[Imax1 Vmax1 Imax2 Vmax2];

%% BATTERY Sizing

DOD=0.6; %Deep of Discharge
MinCBa1=zeros(1,2); %Inicializating
for i = 1:2
    V=[12;14]; %[V]
    D1=1; %[days]
    MinCBa1=((DDT/n)./(DOD*V))*D1; %Minimum Required Battery Capacity [Ah]
    B1=[V MinCBa1];
end
for i = 1:2
    V=[12;14]; %[V]
    D2=0.16; %[days]
    MinCBa2=((DDT/n)./(DOD*V))*D2; %Minimum Required Battery Capacity [Ah]
    B2=[V MinCBa2];
end

ResultsBattery=[V MinCBa1 MinCBa2];

```

%% CABLE SIZING & COST %% POWER LOSSES & COST

%Cable Cost

```

if cablesection <=5;
    cableprice=1.20;
elseif (5<cablesection)&&(cablesection <=9);
    cableprice=1.50;
elseif (9<cablesection)&&(cablesection <=15);
    cableprice=3.30;
elseif 15<cablesection;
    cableprice=3.70;
end
    cablecost=cableprice*cablelength; %Cable Cost [ ]

```

%Annual Cost of the Losses

```

PVPP=(sum(Powers(indexPV)))/1000; %Photo Voltaic Panel Power [KWp]
Losses=(sum(sum(Plosses)))/1000; %KW
HG=5.24; %Hours of Energy Daily Generation (PSH) [Hs]
AE=(PVPP-Losses)*HG*365; %Generated Energy [KWh/year]
AL=Losses*HG*365; %Annual Losses [KWh/year]

```

ALC=(0.1)*AL; *%Annual Cost of the Losses (Electric Tariff=0.1Euro/KWh)*

ResultsCableLoss=[cablelength npv Vbat cablesection cablecost AE AL ALC];

%% RESULTS

```

disp( '——PV_Panels_Sizing——' )
Table1=array2table(ResultsPVP, 'VariableNames',{ 'DDT', 'MinWp', 'NofPVP', 'PVPT', 'D
disp( '——Charge_Controller_Sizing——' )
Table2=array2table(ResultsChC, 'VariableNames',{ 'Imax1', 'Vmax1', 'Imax2', 'Vmax2' })
disp( '——Battery_Sizing——' )
Table3=array2table(ResultsBattery, 'VariableNames',{ 'V', 'MinCBa1', 'MinCBa2' })
disp( '——SUMMARY——' )
Table4=array2table(ResultsCableLoss, 'VariableNames',{ 'L', 'npv', 'Vbat', 'CableSect

```


Appendix C

LVDC Microgrids: PVSHS Sizing - Loop - MATLAB Code

```
%% LVDC Microgrids: PVSHS Sizing - Loop
```

```
%% LVDC Microgrids: PVSHS Sizing - Loop
```

```
close all  
converter = 'no';  
Vbat = 12;           % Volts  
Tc = 25.15;          % C  
G = 1000;             % W/m^2  
Pload = -50;  
npv=4;  
  
load('distances.mat'); % Matrix with distances between nodes  
load('type.mat');      % Vector specifying pv(1), load(-1), battery(0)  
pvnumber;
```

```
%% INITIAL DATA
```

```
section = [4 6 10 16]'; % [mm2]  
rho_Cu = 0.0171;        % [Ohm mm2/m]
```

```
%% 4 PVP
```

```
%% vector initialization
```

```
drop = zeros(length(section),1);
```

```
node = drop;
```

```
loss = drop;
```

```
%%
```

```
for num = 1:length(section)
```

```
    % IMPORTANT: multiply by 2 the cable resistance (representing the
```

```

% 2-side resistances of the circuit
r = 2*rho_Cu/section(num);
solver;
[drop(num),node(num)] = max(abs(dV(:,2)));
loss(num) = Losses;
disp('Section');
disp(section(num));
cablecost=distance*[1.20 1.50 3.00 3.30]';
lossescost1=((0.1/1000)*5.24*365*loss);
close all

end

Power4PV=sum(Powers(indexPV))
Results4PVP = table(section,loss,cablecost,lossescost1)

%% LVDC Microgrids: PVSHS Sizing - Loop

close all
converter = 'no';
Vbat = 12;           % Volts
Tc = 25.15;          % C
G = 1000;            % W/m^2
Pload = -50;
npv=5;

load('distances.mat'); % Matrix with distances between nodes
load('type.mat');      % Vector specifying pv(1), load(-1), battery(0)
pvnumber;

%% INITIAL DATA

section = [4 6 10 16]'; % [mm2]
rho_Cu = 0.0171;        % [Ohm mm2/m]

%% 5 PVP

%% vector initialization
drop = zeros(length(section),1);
node = drop;
loss = drop;
%%
for num = 1:length(section)
    % IMPORTANT: multiply by 2 the cable resistance (representing the
    % 2-side resistances of the circuit
    r = 2*rho_Cu/section(num);
    solver;
    [drop(num),node(num)] = max(abs(dV(:,2)));

```

```

    loss(num) = Losses;
    disp('Section');
    disp(section(num));
    cablecost=distance*[1.20 1.50 3.00 3.30]';
    lossescost2=((0.1/1000)*5.24*365*loss);
    close all

end

Power5PV=sum(Powers(indexPV))
Results5PVP = table(section,loss,cablecost,lossescost2)

%% LVDC Microgrids: PVSHS Sizing - Loop

close all
converter = 'no';
Vbat = 12;           % Volts
Tc = 25.15;          % C
G = 1000;            % W/m^2
Pload = -50;
npv=6;

load('distances.mat'); % Matrix with distances between nodes
load('type.mat');      % Vector specifying pv(1), load(-1), battery(0)
pvnumber;

%% INITIAL DATA

section = [4 6 10 16]'; % [mm2]
rho_Cu = 0.0171;        % [Ohm mm2/m]

%% 6 PVP

%% vector initialization
drop = zeros(length(section),1);
node = drop;
loss = drop;
%%
for num = 1:length(section)
    % IMPORTANT: multiply by 2 the cable resistance (representing the
    % 2-side resistances of the circuit
    r = 2*rho_Cu/section(num);
    solver;
    [drop(num),node(num)] = max(abs(dV(:,2)));
    loss(num) = Losses;
    disp('Section');
    disp(section(num));
    cablecost=distance*[1.20 1.50 3.00 3.30]';
    lossescost3=((0.1/1000)*5.24*365*loss);

```

```
close all

end

Power6PV=sum(Powers(indexPV))
Results6PVP = table(section,loss,cablecost,lossescost3)
```

Appendix D

LVDC Microgrids: PVSHS LCOEMix - MATLAB Code

```
%% LVDC Microgrids: PVSHS LCOE
```

```
solver;  
sum(Powers(indexPV));  
sum(sum(Plosses));  
cablelength=distance;  
cablesection=section;  
npv;
```

```
%% INITIAL DATA
```

```
% PVSHS Technical Data
```

```
PVPPp=npv*25/1000; %PhotoVoltaic Panel Power Peak [KWp]  
PVPP=(sum(Powers(indexPV)))/1000; %PhotoVoltaic Panel Power [KWp]  
Losses=(sum(sum(Plosses)))/1000; %KW  
HG=5.24; %Hours of Energy Daily Generation (PSH) [Hs]  
E=(PVPP-Losses)*HG*365; %Generated Energy [KWh/year]  
Y=((PVPP-Losses)*HG*365)/PVPPp; %Initial Yield [KWh/KWp/year]
```

```
% PVSHS Economic Data
```

```
N=25; %PVP Life [years]  
RV=0; %Residual Value [ /KWp]  
r=10/100; %Discount Rate [%]  
D=0.5/100; %System Degradation Rate [%]
```

```
% PVSHS Component Data
```

```
INV=0; %Inverter [Yes or No]  
COM=0; %Cost of Operation and Maintenance [Yes or No]
```

```
% PVSHS Comparison Index
```

```
RCC=1; %Regional Comparison Coefficient LCOE [Ad] (Asia)  
TCC=1; %Temporal Comparison Coefficient [Ad]
```

ED=1.161; %Currency Relationship: Euro-Dolar [Ad] (June 2018)
CR=97.44; %Currency Relationship: Euro-Local Currency [Ad] (June 2018)

%% CAPEX – CAPital EXpenditures

% Data and Previous Calculations

%PVPanel Cost >1KW

PVPCg=350/ED; %PVPanel Cost [/KWp] (350 [\$/KWp])

%PVPanel Cost <1KW

PVPCb=1900; %PVPanel Cost [/KWp]

%Inverter Cost >1KW

ICg=(150/ED)*INV*2; %Inverter Cost [/KWp] X2 For the Lifetime (150 [\$/KWp])

%Inverter Cost <1KW

ICb=430*INV*2; %Inverter Cost [/KWp] X2 For the Inverter Lifetime

%Balance of System Cost (BoSC) >1KW

BoSSg=(110/ED); %BoS Structure Cost [/KWp] (110 [\$/KWp])

BoSEg=(265/ED); %BoS Electric Cost [/KWp] (265 [\$/KWp])

BoSCg=BoSSg+BoSEg; %Total BoS Cost [/KWp]

%Balance of System Cost (BoSC) <1KW

%BoS Structure Cost (BoSS)

MSCb=(110/ED); %Mounting Structures Cost [/KWp]

BoSSb=MSCb; %[/KWp]

%BoS Electric Cost (BoSE)

BCb=160*3*HG; %Battery Cost [/KWp] X3 For the Battery Lifetime

ChCCb=200; %Charge Controller Cost (MPPT or PWM) [/KWp]

if cablesection<=5

cableprice=1.20;

elseif (5<cablesection)&&(cablesection<=9)

cableprice=1.50;

elseif (9<cablesection)&&(cablesection<=15)

cableprice=3.00;

elseif 15<cablesection

cableprice=3.30;

end

cablecost=(cableprice*cablelength); %Cable Cost []

cableCAPEX=(cableprice*cablelength)/PVPPp; %Cable Cost [/KWp]

BoSEb=BCb+cableCAPEX+ChCCb; %[/KWp]

BoSCb=BoSSb+BoSEb; %[/KWp]

%Engineering and Installation Cost [/KWp]

EIC=48/ED; %[C /KWp] (48 [\$/KWp])

% CAPEX Calculation

```

if PVPPp>=1
    PVPC=PVPCg; IC=ICg; BoSC=BoSCg;
elseif 1>PVPPp
    PVPC=PVPCb; IC=ICb; BoSC=BoSCb;

    CAPEX=(PVPC+IC+BoSC+EIC); %CAPEX [ /KWp]
end

TFC=CAPEX*PVPPp; %Total Fixed Costs [ ]
TFClc=TFC*CR; %Total Fixed Costs [Local Currency]

ResultsCAPEX=[CAPEX TFC TFClc];
disp( '——CAPEX——' )
Table1=array2table(ResultsCAPEX, 'VariableNames',{ 'CAPEX', 'FixedCost', 'FixedCostL

%% OPEX – OPerational EXpenditures

% Data and Previous Calculations
OMC=21/ED; %Operational and Maintenance Costs [ /KWp/year] (21 $/KWp/year))

% OPEX Calculation
OPEX=OMC*COM; %OPEX [ /KWp/year]
OMAC=OPEX*PVPPp; %OM Annual Costs [ /year]
OMAClc=OMAC*CR; %OM Annual Costs [Local Currency/year]

ResultsOPEX=[OPEX OMAC OMAClc];
disp( '——OPEX——' )
Table2=array2table(ResultsOPEX, 'VariableNames',{ 'OPEX', 'OMACost', 'OMACLC' })

%% Variable Costs & Generated Energy

%Annual Variable Costs
AVC1=0;
AVC2=0;
%Annual Generated Energy
AGE1=0;
AGE2=0;

for n = 1:N
    AVC1=AVC1+((OPEX-RV)/((1+r)^n)); %Annual Variable Costs [ /year]
    AVC2=AVC2+((OMAC-RV)/((1+r)^n)); %Annual Variable Costs [ /year]
    AGE1=AGE1+(((Y*(1-D)^n)/((1+r)^n))); %Annual Generated Energy [KWh/year]
    AGE2=AGE2+(((E*(1-D)^n)/((1+r)^n))); %Annual Generated Energy [KWh/year]
end

%% LCOE – LEVELIZED COST OF ENERGY

LCOE1=((CAPEX+AVC1)/AGE1)*RCC*TCC %LCOE [ /KWh]

```


$$LCOE2 = ((TFC + AVC2) / AGE2) * RCC * TCC \quad \%LCOE \quad [\quad /KWh]$$

```
ResultLCOEMix=[cablelength Vbat npv cablesection CAPEX OPEX LCOE1];
```

```
disp('—SUMMARY—')
```

```
Table3=array2table(ResultLCOEMix, 'VariableNames',{ 'cablelength ', 'Vbat ', 'npv ', 'cables
```

Appendix E

LVDC Microgrids: PVSHS LCOEMix Loop - MATLAB Code

```
%% LVDC Microgrids: PVSHS LCOE - Loop
```

```
close all  
converter = 'no';  
Vbat = 12;           % Volts  
Tc = 25.15;          % C  
G = 1000;             % W/m^2  
Pload = -50;  
npv=4;  
  
load('distances.mat'); % Matrix with distances between nodes  
load('type.mat');      % Vector specifying pv(1), load(-1), battery(0)  
pvnumber;
```

```
%% INITIAL DATA
```

```
sec = [4 6 10 16]'; % [mm2]  
rho_Cu = 0.0171;    % [Ohm mm2/m]
```

```
%% 4 PVP
```

```
%% vector initialization  
drop = zeros(length(sec),1);  
node = drop;  
loss = drop;  
cap = drop;  
op=drop;  
lco=drop;
```

```

%%
for num = 1:length(sec)
    % IMPORTANT: multiply by 2 the cable resistance (representing the
    % 2-side resistances of the circuit
    section = sec(num);
    r = 2*rho_Cu/section;
    solver;
    cablecost=distance*[1.20 1.50 3.00 3.30]';
    [drop(num),node(num)] = max(abs(dV(:,2)));
    loss(num) = Losses;
    LCOEMix;
    [drop(num),node(num)] = max(abs(dV(:,2)));
    cap(num) = CAPEX;
    [drop(num),node(num)] = max(abs(dV(:,2)));
    op(num) = OPEX;
    [drop(num),node(num)] = max(abs(dV(:,2)));
    lco(num) = LCOE1;
    disp('Section')
    disp(section)
    close all

end

Results4PVP = table(sec,cap,op,lco)

%% LVDC Microgrids: PVSHS LCOE - Loop

close all
converter = 'no';
Vbat = 12;           % Volts
Tc = 25.15;          % C
G = 1000;             % W/m^2
Pload = -50;
npv=5;

load('distances.mat'); % Matrix with distances between nodes
load('type.mat');       % Vector specifying pv(1), load(-1), battery(0)
pvnumber;

%% INITIAL DATA

sec = [4 6 10 16]';      % [mm2]
rho_Cu = 0.0171;         % [Ohm mm2/m]

%% 5 PVP

%% vector initialization
drop = zeros(length(sec),1);

```

```

node = drop;
loss = drop;
cap = drop;
op=drop;
lco=drop;
%%%
for num = 1:length(sec)
    % IMPORTANT: multiply by 2 the cable resistance (representing the
    % 2-side resistances of the circuit
    section = sec(num);
    r = 2*rho_Cu/section;
    solver;
    cablecost=distance*[1.20 1.50 3.00 3.30]';
    [drop(num),node(num)] = max(abs(dV(:,2)));
    loss(num) = Losses;
    LCOEMix;
    [drop(num),node(num)] = max(abs(dV(:,2)));
    cap(num) = CAPEX;
    [drop(num),node(num)] = max(abs(dV(:,2)));
    op(num) = OPEX;
    [drop(num),node(num)] = max(abs(dV(:,2)));
    lco(num) = LCOE1;
    disp('Section')
    disp(section)
close all

end

Results5PVP = table(sec,cap,op,lco)

%% LVDC Microgrids: PVSHS LCOE - Loop

close all
converter = 'no';
Vbat = 12;           % Volts
Tc = 25.15;          % C
G = 1000;             % W/m^2
Pload = -50;
npv=6;

load('distances.mat'); % Matrix with distances between nodes
load('type.mat');      % Vector specifying pv(1), load(-1), battery(0)
pvnumber;

%% INITIAL DATA

sec = [4 6 10 16]';    % [mm2]
rho_Cu = 0.0171;       % [Ohm mm2/m]

```

%% 6 PVP

%% vector initialization

drop = **zeros**(**length**(sec),1);

node = drop;

loss = drop;

cap = drop;

op=drop;

lco=drop;

%%

for num = 1:**length**(sec)

*% IMPORTANT: multiply by 2 the cable resistance (representing the
% 2-side resistances of the circuit*

section = **sec**(num);

r = 2*rho_Cu/section;

solver;

cablecost=distance*[1.20 1.50 3.00 3.30]';

[drop(num),node(num)] = **max**(**abs**(dV(:,2)));

loss(num) = Losses;

LCOEMix;

[drop(num),node(num)] = **max**(**abs**(dV(:,2)));

cap(num) = CAPEX;

[drop(num),node(num)] = **max**(**abs**(dV(:,2)));

op(num) = OPEX;

[drop(num),node(num)] = **max**(**abs**(dV(:,2)));

lco(num) = LCOE1;

disp('Section')

disp(section)

close all

end

Results6PVP = **table**(sec, cap, op, lco)

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